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RESEARCH MEMORANDUM

ICING CHARACTERISTICS AND ANTI-ICING HEAT REQUIREMENTS
FOR HOLLOW AND INTERNALLY MODIFIED GAS-HEATED
INLET GUIDE VANES

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RESEARCH MEMORANDUMICING CHARACTERISTICS AND ANTI-ICING HEAT REQUIREMENTS FOR HOLLOW
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SUMMARY

A two-dimensional inlet-guide-vane cascade was investigated to determine the effects of ice formations on the pressure losses across the guide vanes and to evaluate the heated gas flow and temperature required to prevent icing at various conditions. A gas flow of approximately 0.4 percent of the inlet-air flow was necessary for anti-icing a hollow guide-vane stage at an inlet-gas temperature of 500° F under the following icing conditions: air velocity, 280 miles per hour; water content, 0.9 gram per cubic meter; and inlet-air static temperature, 0° F. Also presented are the anti-icing gas flows required with modifications of the hollow internal gas passage, which show heat-input savings greater than 50 percent.

INTRODUCTION

Ice formations on turbojet-engine inlet guide vanes cause a pressure reduction in the air entering the first rotor stage. This pressure reduction may have the following effects, which when combined may become serious enough to necessitate shutdown of the engine: reduced engine thrust, increased fuel consumption, and increased tail-pipe temperature.

The investigation reported herein was conducted at the NACA Lewis laboratory to determine the magnitude of pressure losses caused by various ice formations on an unheated inlet guide-vane cascade and the heat required to prevent ice formations. A convenient source of heat for hollow inlet guide vanes is hot air bled from the compressor outlet or hot gas bled from the combustion-chamber outlet. In this investigation, heated air was utilized to determine the flow rates and temperatures required to prevent icing. Two guide vanes with internal modifications were investigated and compared with a hollow vane to evaluate the reductions in heating rates possible with internal-flow-passage alterations.

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The research installation comprised a fixed two-dimensional cascade of five vanes that spanned a short rectangular duct mounted in the 6- by 9-foot icing research tunnel. The vane chord was $2\frac{3}{8}$ inches, the gap between vanes was $3\frac{1}{8}$ inches, and the span was 5.9 inches. Vanes of smaller chord and gap size may be more effective aerodynamically, but will become more quickly blocked with ice under icing conditions. In addition, smaller vanes are more difficult to equip with internal instrumentation.

The range of conditions investigated was as follows:

Inlet-air velocity, mph	178 to 304
Inlet-air total temperature, °F	-23 to 23
Water content, gram/cu m	0.3 to 1.0
Pressure altitude, ft	below 3500

Current turbojet engines utilize inlet-air velocities greater than those obtainable in the icing research tunnel; from the velocities investigated, however, the anti-icing requirements at higher air-velocities may be estimated.

Heat requirements for icing protection of inlet guide vanes have also been obtained in a concurrent investigation (reference 1) utilizing electrical resistance elements imbedded in a solid metal guide vane.

APPARATUS AND MODELS

The installation in the icing research tunnel of the five-guide-vane cascade and the surrounding duct is shown in figure 1. The four tubes upstream of the vanes and the horizontal and vertical rakes downstream of the vanes were used to measure the pressure loss across the vanes. Additional wall static taps were provided for the pressure study. The horizontal rake was gas-heated and all total-pressure tubes were electrically heated. The four duct walls, the inlet lips, and the center-support fairing were anti-iced by hot gas independent of the vane heating system. The guide vanes were thus the only surfaces to collect ice during heat-off operation of the vanes.

The heat supply for the five guide vanes consisted of compressed air heated in a heat exchanger by combustion products of a jet burner. Cold air and valving for mixing hot and cold gas as desired, as well as a regulator for controlling the flow, were provided. The heated gas was distributed through a manifold to the five vanes; it then flowed

upward through the vanes into an outlet passage that exhausted into the tunnel air. The gas flow for the center vane was determined by a calibrated metering box in the line. The gas temperature was measured by thermocouples in the inlet manifold, the center-vane inlet and midpoint, and by a five-point thermocouple rake at the outlet. The center vane was insulated at both ends from the duct walls and manifolds.

Surface-temperature measurements were obtained at midspan of the center vane by flush thermocouples installed in small slots milled into the steel skin of the vane. The thermocouple junctions were soldered into the slots and the surface faired smooth. The thermocouple leads were encased in small metal tubes that extended from the junctions in a spanwise direction in the slots for approximately 10 tube diameters; the tubes were next brought to the vane outlet through the gas-flow passage. The leads then joined a terminal strip located in the outlet-gas manifold.

The chordwise location of the surface-temperature thermocouples, as well as sectional views of the three sheet-steel vanes investigated, is shown in figure 2. The over-all dimensions of the three vanes were: chord, 2.38 inches; solidity, 0.76; span exposed to air flow, 5.90 inches; angle of attack, 15° ; external area, 28.9 square inches; skin thickness, 0.020 inches; and leading-edge-cylinder diameter, 0.18 inches. Additional information about the vanes is presented in the following table:

Vane	Internal flow area (sq in.)	Wetted perimeter (in.)
1	0.343	4.78
2	.210	8.43
3	.220	6.38

Vanes 2 and 3 were designed with external contours the same as those of vane 1 to illustrate the effect of modifications in the internal gas passage. Vane 2 had a 0.020-inch-thick sheet-steel fin soldered to the vane skin at the internal leading edge and near the trailing edge on the concave surface. The fin supported a spanwise insert of sheet metal enclosing a dead air space, which reduced the net flow-passage area (fig. 2(b)). Vane 3 had a spanwise insert of insulating material attached to the convex side of the vane (fig. 2(c)). For the external air-velocity survey, an additional vane was provided with flush static-pressure taps in the same positions as the surface-temperature thermocouples of vane 1.

CONDITIONS AND PROCEDURE

For evaluating the heating and icing characteristics of the guide vanes investigated, the following nominal conditions were imposed:

Inlet-air total temperature (°F)	Water content (gram/cu m)	Inlet-air velocity (mph)		
		Vane		
		1	2	3
-20	0.9	280	180	
0	0.4	180		
		280		
22	0.9	180	180	180
		280	280	280
	0.4	180	180	180
		280	280	280
	0.9	180		
		280		

A calibration of the water content of the tunnel air was made just upstream of the vane duct for the range of air temperatures. The variation in liquid-water content is shown in figure 3 as measured by standard rotating-cylinder technique when the water flow through the nozzles was held constant and the air temperature varied. The air was saturated at all temperatures prior to sprays and the velocity was constant; therefore, the liquid-water content should also have been approximately constant. The reduction in measured liquid-water content at temperatures approaching the freezing point could be due to water blow-off from the cylinders occurring because of slow freezing rates, and the reduction at lower temperatures could be due to freeze-out of the spray droplets before reaching the models. The calibration shown in figure 3 was used in conjunction with the spray water-flow readings to determine the effective water content of the air passing through the guide vanes. The mean droplet diameter was in the range of 10 to 15 microns.

In order to determine the aerodynamic losses caused by ice formations on the guide vanes, ice was allowed to accumulate on the unheated vanes and pressures upstream and downstream of the vanes were obtained at short time intervals during the icing period. The pressure readings were usually terminated before any ice accumulations were shed from the vanes in order to safeguard the total-pressure rake. Occasional difficulty was experienced in maintaining the total-pressure tubes ice-free, with the result that some vane wakes were not so well defined as planned.

The heating rates required to prevent icing on the guide vanes were determined by progressively decreasing the gas temperature at constant gas and air flow. Visual observations of the vane surfaces helped to locate the marginal anti-icing heat requirements, but such observations were subject to error when dense spray clouds caused low visibility. Surface temperatures taken at critical points provided a means of interpolation between readings at different heating intensities; the approach to freezing temperatures on the vanes was thereby more accurately determined.

RESULTS AND DISCUSSION

Aerodynamic Characteristics

The velocity distribution over the external surfaces of the guide vanes investigated is shown in figure 4. No discernible change in the velocity distribution occurred for the range of air velocities investigated in both wet and dry air.

The chordwise variation of the internal-gas-velocity profile is shown in figure 5 for the three guide vanes investigated. The velocities were determined at the outlet end of the vanes at points equidistant from the passage side walls and showed little change in profile for the selected range of gas flows and temperatures. Vane 2 necessitated two velocity profiles, one on each side of the center insert. The velocity profile normal to the side walls was not determined, although large gradients near the walls would be expected.

The wedge-shaped trailing portion of the vanes offered such resistance to gas flow that the velocity was greatly reduced in this region. The gas velocity through vane 1 at a point 60 percent downstream of the internal-passage leading edge was approximately 1.2 times the mass mean velocity and then decreased almost linearly to 0 at the internal trailing edge. At an internal chord length of 0.74, the velocity through the concave side of vane 2 fell to 0 at the junction of the internal fin and concave wall of the vane. The velocity distribution through vane 3 and the convex side of vane 2, however, was considerably improved; it was above the mean mass velocity back to 92 percent of the internal chord. Elsewhere in the internal passages, the principal deviation between the vanes was the tendency of the two modified vanes to have gas velocity ratios in excess of those for vane 1. Consequently, more peaked velocity profiles between passage side walls would be expected for vanes 2 and 3 than for vane 1, with larger percentages of the narrower passages occupied by low-velocity wall flow.

Icing Characteristics and Pressure Losses

Unheated vanes. - The nature of the ice formations that accumulate on unheated guide vanes can be observed in figure 6 for eight icing conditions and various icing times. A distinct difference is apparent between the formations at a total air temperature of 0° F and those at 22° F. Because the ice formations built out laterally at the high air temperature, a wide and nodular front was presented to the air stream; whereas at 0° F, where the ice built directly forward into the air stream, the leading edge maintained a regular, wedge-shaped cross section. The variables water content, air velocity, and icing time contributed principally to the amount of ice accretion.

The pressure losses associated with these ice formations are presented in figure 7, where the pressure loss is plotted as a function of time under icing conditions. The losses increased rapidly at the 22° F air temperature, especially at a water content of 0.9 gram per cubic meter; a maximum of 54 percent was reached in an icing time of 3 minutes. The pressure loss showed a minor variation with air velocity, a marked variation with water content, and an approximately linear variation with icing time. From figure 7 and the photographs in figure 6, the losses at the higher water content were serious even at an air temperature of 0° F; greater and more rapid losses may be anticipated for cascades with gap and chord sizes smaller than those reported herein.

Heated vanes. - Without ice on the vanes, the pressure losses ranged from 4 to 8 percent across the cascade. The losses with marginal and submarginal anti-icing were briefly investigated. With insufficient heating, the vanes iced as shown in figure 8. The mid-chord regions of the vanes were ice-free, the leading edges had slight deposits, and the trailing portions had considerably more ice. When the heating was submarginal, the pressure loss was increased approximately 4 percent more by the ice shown in figure 8(a) than for the uniced condition. At conditions nearer the marginal heating level, the residual ice deposits were small and presented the spotty appearance shown in figure 8(b). Because of the upward gas flow through the vanes and the consequent spanwise temperature drop, the gas temperature was lowest at the top of the vane; heating insufficient to prevent ice on the top half of the vanes resulted.

Dry-Air Analysis

Preliminary investigation. - Prior to a determination of the anti-icing heat requirements, the guide vanes were investigated for

heating characteristics in dry air. Conduction effects at the vane ends were briefly investigated by heating the vanes at zero air velocity across the vanes. The end effects proved negligible. Another run was made with unheated vanes to determine the datum air temperature, which is equivalent to the adiabatic surface temperature. The chordwise surface temperatures were nearly constant and averaged 4° and 1.5° F below the tunnel total temperature for air velocities of 280 and 180 miles per hour, respectively.

Surface-temperature rise. - In dry air flow with continuous heating, the surface-temperature rise above the datum air temperature provides a direct comparison of the external heat-transfer rate between vanes of the same outside shape, but different internal configurations, subjected to the same flow conditions. Such a comparison is made in figure 9 for vanes 1, 2, and 3 at 298 miles per hour air velocity and heated by a gas flow of 120 pounds per hour with a mean gas temperature approximately 195° F above the datum air temperature. Hollow vane 1 has considerably less heat transfer than the two modified vanes; the difference is greater at the trailing and leading edges. Vane 3 has reduced heat transfer on the convex surface near midchord because of the insert, whereas vane 2 in this region has a wasteful expenditure of heat, as shown by the peak in surface-temperature rise. Vane 3 displays a slight advantage over vane 2 at the trailing edge.

Modification effectiveness. - The relative effectiveness of the modified vanes compared with the hollow vane in regard to heat transfer through the vane metal under the same gas- and air-flow conditions is derived in reference 2. The relative modification effectiveness, or the ratio of internal effective conductance of the modified vane to that of the unmodified vanes, is expressed as

$$\frac{(h_g A_g)_{\text{mod}}}{(h_g A_g)_u} = \frac{(t_s - t_a)_{\text{mod}} (t_{g,m} - t_s)_u}{(t_s - t_a)_u (t_{g,m} - t_s)_{\text{mod}}} \quad (1)$$

(All symbols used in this report are defined in the appendix.) This effectiveness is plotted in figure 10 against the mass-velocity ratio $g p_0 v_0 / G_u$ for the leading edges and for average surface values of vanes 2 and 3. The trends are similar to those presented in reference 2 for symmetrical airfoils of 10-inch chord length. The guide-vane modifications investigated herein are less effective than the modifications in the airfoils of reference 2 mainly because the narrow leading- and trailing-edge portions of the gas passage through the vanes do not allow sufficient space for finning to the extent used in

the symmetrical airfoils. For flow conditions typical of normal engine operation, the following values of relative modification effectiveness are representative:

Vane	Position	Effectiveness
		$\frac{(h_g A_g)_{\text{mod}}}{(h_g A_g)_u}$
2	Surface average	1.8
	Leading edge	1.9
	Trailing edge	1.4
3	Surface average	1.4
	Leading edge	1.7
	Trailing edge	1.7

The relative merits of the internal modifications in increasing heat transfer at the critical leading- and trailing-edge regions are shown in this table. Vane 2 increased the heat-transfer average over the surface by 80 percent over that for vane 1, yet increased the trailing-edge heat transfer only 40 percent. Vane 3, however, was more efficient in that it increased the surface average only 40 percent and the leading and trailing edges by 70 percent. If equivalent blocking effects are assumed for the inserts in vanes 2 and 3, the addition of a leading-edge fin to vane 2 apparently increases the leading-edge heat transfer, whereas the trailing-edge fin actually decreases the heat transfer by blocking off and decreasing the gas velocity in the trailing-edge section.

Internal and external flow exponents. - Another important heating characteristic of the vanes may be evaluated from dry-air data, namely, the variation of internal heat-transfer coefficient with the gas flow. This variation may be determined by the method given in detail in reference 2. The exponents of gas flow in the equation for the gas heat-transfer coefficient h_g are given by the slopes of the lines in figure 11(a). The three vanes have a gas-flow exponent of approximately 0.8. Established formulas for fully developed turbulent flow in pipes have the same flow exponent, and the following equation will therefore be used for the subsequent analysis of the wet-air and anti-icing data:

$$h_g = 4.1 \times 10^{-4} T_g^{0.3} \frac{w^{0.8} P^{0.2}}{A_p} \quad (2)$$

From the dry-air data, the exponent of external air flow may be obtained as a function of the air heat-transfer coefficient. The pipe-flow entrance effects were assumed negligible because the inlet portion of the vanes (approximately 0.75 in. long) was not exposed to external air flow. Figure 11(b) yields several values of this exponent over a range of gas flows. The average exponent for air flow over both faces of the three vanes was approximately 0.64. This power is midway between 0.5 for laminar flow and 0.8 for completely turbulent flow. It is probable, therefore, that turbulent flow existed over a large part of the convex surface and laminar flow over much of the concave surface. Under icing conditions, the extent of turbulent flow would doubtless be considerably increased.

Internal heat-transfer coefficient. - The average external heat-transfer coefficient over the vanes was also determined from the dry-air data. The following heat-balance equation was utilized in calculating the external heat-transfer coefficient:

$$w c_p (t_{g,i} - t_{g,o}) = h_{a,av} A_a (t_{s,av} - t_a) \quad (3)$$

The average dry-air coefficients were approximately 44 and 64 Btu per hour per square foot per °F for air velocities of 180 and 280 miles per hour, respectively.

Effective gas-passage perimeter. - In calculating heat transfer through the vane metal, the following heat-balance equation is frequently used:

$$h_g A_g (t_{g,m} - t_{s,av}) = h_{a,av} A_a (t_{s,av} - t_a) \quad (4)$$

When equation (2) is used to determine h_g , the proper values of the gas heat-transfer area and perimeter are required. The wetted perimeter is not a suitable heat-transfer perimeter for irregular gas passages, especially for those of vanes 2 and 3. The effective value of A_g can be evaluated approximately, however, from experimentally observed temperatures, values of $h_{a,av}$ from the dry-air investigation of external heat transfer, and values of h_g calculated from equation (2). The gas heat-transfer area is then set equal to the product of an effective perimeter and the span; equation (4) accordingly becomes

$$4.1 \times 10^{-4} T_{g,m}^{0.3} w^{0.8} \frac{P_e^{0.2}}{A_p} L P_e (t_{g,m} - t_{s,av}) = h_a L S (t_{s,av} - t_a) \quad (5)$$

or,

$$P_e = \left(\frac{SA_p}{4.1 \times 10^{-4}} \right)^{0.833} \left[\frac{h_a (t_{s,av} - t_a)}{T_{g,m}^{0.3} w^{0.8} (t_{g,m} - t_{s,av})} \right]^{0.833} \quad (6)$$

By use of temperature data obtained in dry-air flows, the effective gas-passage perimeter was calculated for the three vanes and found to be substantially independent of air velocity and gas flow. The following effective-perimeter values were obtained for heat balances under wet-air and icing conditions and are compared with the corresponding wetted perimeters:

Vane	Effective gas passage perimeter (in.)	Wetted perimeter (in.)
1	4.00	4.78
2	4.27	8.43
3	3.73	6.38

These values show an effective increase in heat-transfer area over that of vane 1 because of fins in vane 2 and a decrease because of the unheated area of vane 3.

Anti-Icing Requirements

Preliminary investigations. - The datum air temperature in wet air was determined for the unheated vanes to be nearly equal to the tunnel total temperature at an air speed of 180 miles per hour and approximately 1° F less at an air speed of 280 miles per hour. With unheated vanes in icing conditions, a surface-temperature rise results because of release of the heat of fusion of the freezing water. At the leading edge, this temperature rise reached a maximum of 10° F.

Variations in leading-edge temperature near marginal heating level. - A time-temperature trace of the leading edge of vane 3 in a severe icing condition is shown in figure 12. In addition, the chordwise surface temperatures are shown at the beginning and after 10 minutes of exposure to the icing condition. The mean-gas-temperature increase during this interval is also shown. Initially the leading-edge temperature is 32° F until an ice covering sufficient to permit melting of the ice at the ice-vane interface has accreted. During this

phase the vane surface temperature increases markedly, to as high as 50° F, until the ice is shed, whereupon the surface returns to the ice point. This natural intermittent ice shedding occurred approximately at 1-minute intervals. As the gas temperature was increased, the peak temperatures prior to shedding decreased, shedding became more rapid, and the surface temperature tended to stabilize at the ice point. With a further increase in gas temperature, the surface became ice-free and the surface temperature rose steadily. During this 10-minute interval, the leading-edge temperature rose from 32° to 37° F, the average chordwise surface temperature rose from 44° to 54° F, but the trailing-edge temperature remained at about 13° F. The trailing portion of the vane remained iced (underheated) throughout this run.

Chordwise temperature distribution. - In icing conditions, the chordwise variation of the heated-surface temperatures is illustrative of the chordwise efficiency of the vanes during anti-icing. Such a variation is shown in figure 13 wherein the three vanes are compared with respect to the variation about the average surface temperatures. The heating rate for the three vanes was such that all the thermocouples were above 32° F and no ice was evident. Because for vane 2 much of the heat is delivered to the convex surface, which is not a critical area, vane 2 is less efficient for anti-icing than vane 1. Based on the average chordwise surface temperature rise, a proportionately smaller temperature rise results at the trailing edge of vane 2 than for vane 1. Vane 3, compared with vane 1, is equally efficient at the trailing edge and considerably more efficient at the leading edge. The reduced surface temperature of vane 3 on the convex surface results in the increased efficiency of vane 3; however, this temperature does not become low enough to constitute a danger from refreezing of runback moisture. The ideal chordwise distribution of surface-temperature ratio $(t_s - t_a)/(t_{s,av} - t_a)$ would be a line constant at a value of 1. In this respect, vane 3 is the best of the three vanes investigated, but could be considerably improved, especially at the trailing edge. This improvement might be accomplished by isolating the trailing portion of the vane with an independent heated gas supply.

The chordwise internal distribution of gas temperature that accompanied the surface-temperature distribution of figure 13 is shown in figure 14. This distribution is similar to the velocity distribution of figure 5.

Heat requirements at spanwise station. - The marginal anti-icing heat requirements are presented on the basis of the sensible heat in the gas stream $w_p(t_g - t_a)$ at a particular spanwise station for which the heating is just sufficient to prevent icing on that station. The

station chosen herein is at midspan where the surface-temperature thermocouples are located. Heat requirements so calculated are independent of span and can be directly applied in design calculations for similar vanes with different spans.

In determining the marginal heat requirements for anti-icing the three vanes at midspan, a suitable criterion is required. Because the trailing edge was the first point to ice when heating was decreased, the heat requirement would logically be based on marginal anti-icing at this point. If the leading edge is heated to the ice-free point, however, the remaining ice on the trailing edge may be considered no hazard for vanes of the size investigated. In figure 8(a), the leading edges are nearly ice-free and the trailing-edge icing is well shown. Two sets of heat requirements were therefore obtained, one for marginal anti-icing at the trailing edge and one for the leading edge. Extensions of the data subsequently presented are based on the conservative trailing-edge criterion.

The average surface temperature of the three vanes at the two marginal anti-icing conditions is shown in figure 15 for datum air temperatures from -21° to 32° F, air velocities of 180 and 280 miles per hour, and a water content of 0.9 gram per cubic meter. A large difference in the average surface temperature is evident between the leading- and trailing-edge ice-free conditions. The inefficiency of vane 2 in heating the trailing edge is also apparent.

The heat requirements at the midspan section for the same conditions as figure 15 are presented in figure 16 with the addition of data for a water content of 0.4 gram per cubic meter. The variation in water content had a slight effect on heat requirements. The heat requirements were generally slightly higher at a water content of 0.9 gram per cubic meter than at 0.4 gram per cubic meter for the ice-free leading-edge condition; however, at the ice-free trailing-edge condition the opposite trend was found. Although the differences were slight and accurate water contents were difficult to maintain, the explanation for the decreased heat requirement with the larger water content at the trailing-edge condition is probably that the increased water runback over the highly heated midchord surfaces resulted in a higher surface temperature at the trailing edge. The heat required to maintain the trailing edges ice-free averaged about 40 percent more than the corresponding requirements for ice-free leading edges.

Because the data for figure 16 were taken at various values of gas flow and temperature, no direct comparison of heat requirements

can be made between the three vanes. A comparison can be made, however, when the same gas flow per unit flow passage area w/A_p is assumed and the heat requirements are calculated accordingly. The data of figure 16(a) are replotted in figure 17(a) with gas flow per unit flow area assumed constant at 6×10^4 pounds per hour per square foot. In making this conversion, the average external surface temperature and the heat-transfer coefficient were assumed to be unaffected and the required mean gas temperature was calculated. The gas flow of 6×10^4 pounds per hour per square foot was chosen for comparison among the vanes because it was near the average flow through the three vanes during the investigation and represented the least change to the data. At the assumed gas flow, the gas velocities were in the low subsonic range and the gas temperatures required to obtain marginal conditions were within limits of practicability for current engines.

From figure 17, vane 2 is seen to require more heating for complete midspan anti-icing than vane 3, although both require considerably less heating than vane 1. At a datum air temperature of 0°F , vane 1 requires internal heat flows of 9200 and 7100 Btu per hour at air flows of 280 and 180 miles per hour, respectively. The heating requirements for vanes 2 and 3 are approximately 40 and 50 percent less, respectively, than for vane 1.

The data of figure 17(a) are shown in figure 17(b) as a function of the gas temperature required for complete midspan anti-icing when the gas flow is proportional to the gas-passage area. Vanes 1 and 2 are practically equivalent in this comparison and vane 3 is slightly improved over the others.

Calculations for ice-free vanes. - Anti-icing heat requirements for different guide vanes may also be compared in terms of the gas flow required for completely ice-free vanes having constant inlet-gas temperatures. Such a comparison depends on specific span length. The subsequent calculations were made for the 5.9-inch span investigated for arbitrarily chosen values of inlet-gas temperature. In these calculations, the average surface temperatures required for midspan anti-icing (fig. 15) were assumed to apply at the vane outlet. An estimated gas flow permitted a determination of the surface-temperature average at the vane-inlet end from the relation

$$h_{g,i} \frac{A_g}{A_a} (t_{g,i} - t_{s,i,av}) = h_{a,av} (t_{s,i,av} - t_a) \quad (7)$$

The average surface temperature for the whole vane was then assumed to be the mean between the inlet and outlet values. From this value, the

gas-temperature drop through the vane was calculated from equation (3) and the outlet-gas temperature determined. A check on the average surface temperature at the outlet, in which equation (7) was used, then indicated whether the initial estimate of gas flow was correct.

The average air heat-transfer coefficients used in the calculations were the effective wet-air coefficients determined from all the runs under icing conditions by a method similar to that described for the dry-air coefficients. Because no consistent trends in the wet-air coefficients resulted for the variations encountered in water contents and surface temperatures, the average external heat-transfer coefficients were assumed constant over the vane span. The average effective wet-air heat-transfer coefficients were found to be approximately 64 and 91 Btu per hour per square foot per $^{\circ}\text{F}$ at air velocities of 180 and 280 miles per hour, respectively.

The results of these calculations are presented in figures 18 to 21. In figure 18, the gas flow ^(*) required for vane anti-icing is plotted as a function of datum air temperature for airspeeds of 180 and 280 miles per hour, and constant inlet-gas temperatures of 500° and 300° F. A significant improvement is shown in all cases with the higher inlet-gas temperature. Calculations for vane 2 (not presented) indicated only slight savings in gas flow over vane 1. The main cause for the deficiency of vane 2 is the wasteful amount of heat transfer through the vane midchord with a large resultant gas-temperature drop in the vane. In order to maintain the necessary gas temperatures at the vane outlet, the gas flow was increased to the extent of nearly nullifying the local advantage of vane 2 over vane 1. Vane 3, however, was greatly improved over vane 1 and required only 50 to 60 percent as much gas flow for the same anti-icing performance. In figure 19 are presented four illustrative gas-flow calculations (from fig. 18) and the corresponding values of gas-temperature drop $t_{g,i}-t_{g,o}$ through the vane. A large range in value of the gas-temperature drop resulted, as exemplified by a range in vane heat-exchanger effectiveness $(t_{g,i}-t_{g,o})/(t_{g,i}-t_a)$ from 0.09 to 0.47.

The heat-input requirement for vane anti-icing is shown in figure 20 as a function of inlet-gas temperature for several values of datum air temperature. When the datum air temperature is 10° F or above, an increase in inlet-gas temperature above 500° F does not appreciably reduce the heat-input requirements; whereas for air temperatures of 0° F or lower, considerable savings are realized by increasing the inlet-gas temperature as much as possible. For example, the requirement for vane 1 for a datum air temperature of 0° F and an

inlet-gas temperature of 300° F is 11,900 Btu per hour; whereas at an inlet-gas temperature of 600° F, the heating required is only 7600 Btu per hour.

The improvement of vane 3 over vane 1 is greatest at the most critical conditions for anti-icing; that is, low datum air temperatures and low inlet-gas temperatures. At a datum air temperature of -20° F and an inlet-gas temperature of 300° F, the heat-input requirement for vane 3 is 39 percent as much as that for vane 1. At 20° F and an inlet-gas temperature of 600° F, the heat-input requirement for vane 3 is 67 percent of that for vane 1.

The gas flow required for guide-vane ice prevention may be expressed in percent of air flow across the vanes. Such a relation is presented in figure 21 as a function of inlet-gas temperature and inlet-air velocity for vanes 1 and 3. At an air velocity of 280 miles per hour (fig. 21(a)), the static air temperature was approximately 9° F lower than the corresponding datum air temperatures. At an inlet-gas temperature of 500° F, the calculated gas flow required for prevention of icing on a guide-vane stage of the hollow-vane type was approximately 0.5 percent of the inlet-air flow at a datum air temperature of 0° F. At an inlet-air static temperature of 0° F, the requirement was approximately 0.4 percent of the air flow. The gas-flow requirement at this condition for a stage of the vane 3 type was approximately 0.2 percent of the air flow.

The gas-to-air flow ratio required for anti-icing a guide-vane stage is given in figure 21(b) as a function of the inlet-air velocity. The relation is shown for vanes 1 and 3 with inlet-gas temperatures assumed constant at 300° and 500° F for a datum air temperature of 0° F and water content of 0.9 gram per cubic meter. An increase with air velocity is shown in the gas-to-air flow percent requirement; this increase resulted from the assumed constant gas-inlet temperature and variable gas flow. By use of figure 21, guide-vane anti-icing heat requirements at inlet-air velocities different from those investigated may be estimated.

Pressure altitudes above 3500 feet were not investigated; however, previous investigations have indicated that anti-icing heat requirements do not vary greatly with altitude alone.

SUMMARY OF RESULTS

In an investigation of the icing characteristics and anti-icing heat requirements for a two-dimensional cascade of gas-heated inlet guide vanes having hollow and modified internal passages, the following results were obtained:

1. Losses in ram pressure up to 54 percent after 3 minutes of icing may result when ice forms on unheated guide vanes. The losses are greater at air temperatures near 22°F than at 0°F because of the characteristic shapes of ice deposits at the two temperatures.

2. At a particular spanwise station, the heat flow in the internal gas stream required to prevent icing on an entirely hollow guide vane was approximately 9200 Btu per hour at a gas temperature of 273°F when the gas flow per unit passage area was at the rate of 6×10^4 pounds per hour per square foot and when the following serious icing condition was imposed: datum air temperature, 0°F ; air velocity, 280 miles per hour; water content, 0.9 gram per cubic meter. For the same condition, the heating requirements were reduced approximately 40 and 50 percent, respectively, when the vanes were modified internally by (a) a spanwise sheet-metal fin attached at the vane internal leading and trailing edges and supporting a center insert, and (b) a spanwise insulating insert attached near midchord to the convex surface. The heating required to completely prevent icing on a guide-vane station was approximately 40 percent more than that required to maintain only an ice-free leading edge.

3. For ice prevention over the complete vane span and chord, the hollow vane required an internal heat flow at the vane inlet of 11,900 and 7600 Btu per hour at inlet-gas temperatures of 300°F and 600°F , respectively, in the serious icing condition previously mentioned. The vane modified with an insulating insert required from 39 to 67 percent as much heat input as the hollow vane, depending on air and gas temperature. When gas at an inlet temperature of 500°F was used, the hollow vane and the vane with an insert required gas flows only 0.4 and 0.2 percent, respectively, of the inlet-air flow for complete ice prevention at an air velocity of 280 miles per hour, a water content of 0.9 gram per cubic meter, and an inlet-air static temperature of 0°F .

4. The vane with fin and insert required nearly as much heat input as the hollow vane because of a high heat-dissipation rate over most of the chordal extent of the vane except at the trailing edge where the internal-gas velocity and temperature were comparatively low. The vane with only an insert had the greatest heating rate at the trailing edge and the greatest efficiency in chordwise heat transfer.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

APPENDIX - SYMBOLS

The following symbols are used in this report:

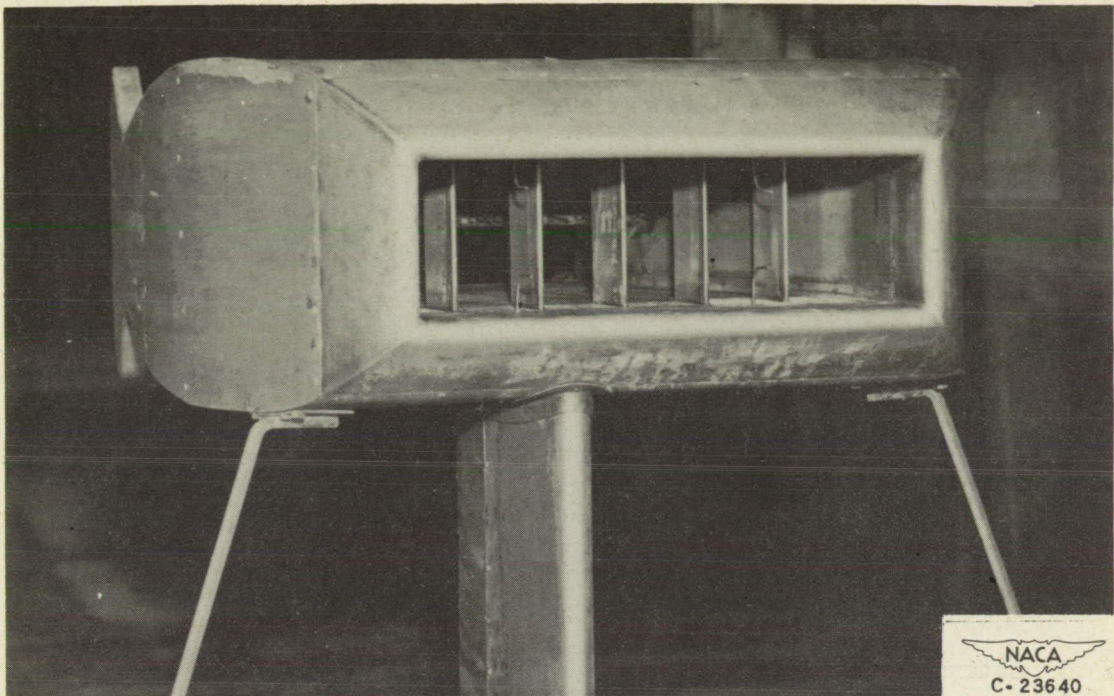
A	heat-transfer area, sq ft
A_p	flow passage net area, sq ft
C	vane chord length, in.
c	internal passage chord length, in.
c_p	specific heat of air at constant pressure, Btu/(lb)(°F)
G	gas flow per unit flow passage area $w/3600 A_p$, lb/(sec)(sq ft)
g	acceleration of gravity, 32.2 ft/sec ²
H	air total pressure, lb/sq ft
h	convective heat-transfer coefficient, Btu/(hr)(sq ft)(°F)
L	vane span, ft
P	internal-passage perimeter, ft
q	dynamic pressure $\left(\frac{1}{2} \rho v^2\right)$, lb/sq ft
S	vane external chordwise-surface length, ft
s	distance along chordwise surface from leading edge, in.
T	absolute temperature, °R
t	temperature, °F
v	velocity, ft/sec
w	gas flow, lb/hr
x	chordwise distance from internal leading edge, in.
ρ	density, lb-sec ² /ft ⁴

Subscripts:

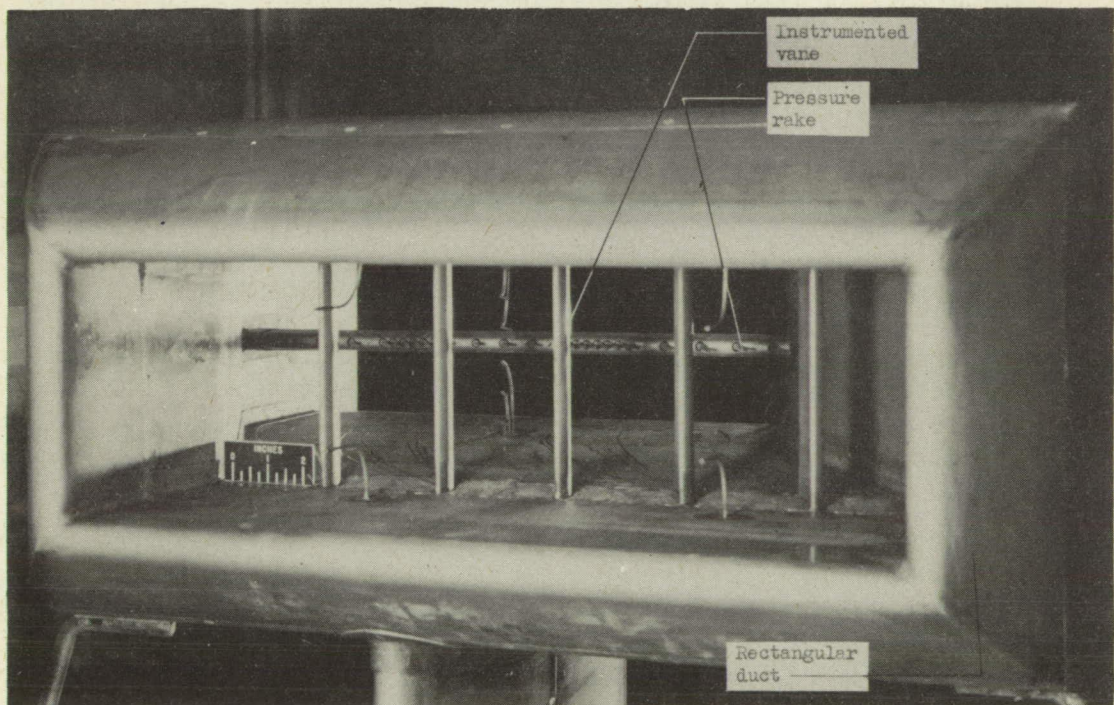
- a external air conditions
- av average
- e effective
- g internal gas conditions
- i inlet end of gas passage
- l local
- m mean between inlet and outlet of gas passage
- mod modified vane
- o outlet end of gas passage
- s external vane surface
- u unmodified vane
- O inlet ambient conditions
- l conditions downstream of vane cascade

REFERENCES

1. von Glahn, Uwe, and Blatz, Robert E.: Investigation of Power Requirements for Ice Prevention and Cyclical De-Icing of Inlet Guide Vanes with Internal Electric Heaters. NACA RM E50H29.
2. Gray, Vernon H.: Improvements in Heat Transfer for Anti-Icing of Gas-Heated Airfoils with Internal Fins and Partitions. NACA TN 2126, 1950.



(a) Left front view.



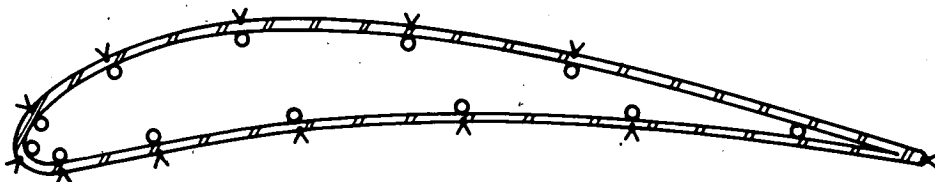
(b) Right front view showing instrumentation.

Figure 1. - Installation of inlet guide vane in icing research tunnel.

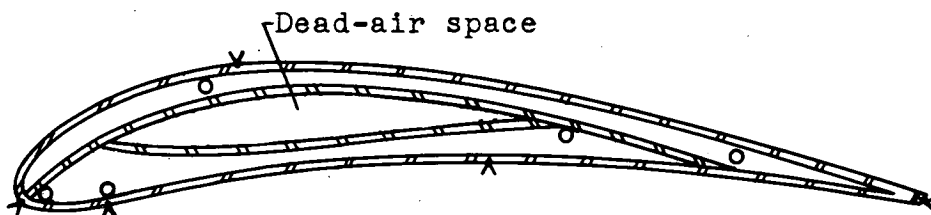
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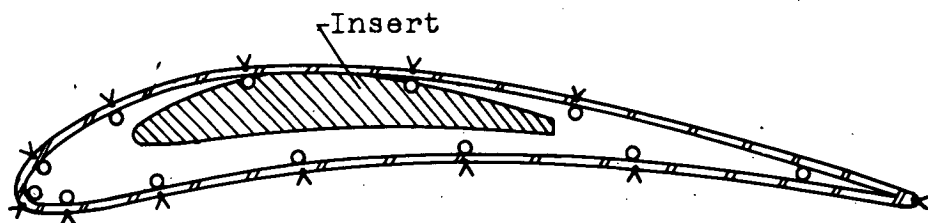
✓ Thermocouple location
○ Thermocouple leads



(a) Vane 1; fully hollow.



(b) Vane 2; internal fin and insert.



(c) Vane 3; internal insulating insert.



Figure 2. - Sections of three gas-heated inlet guide vanes.

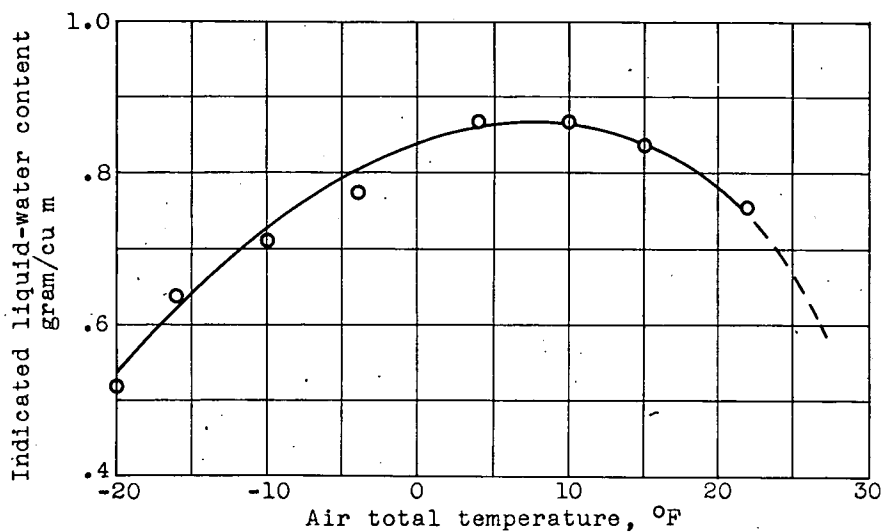


Figure 3. - Variation of indicated liquid-water content with air total temperature for constant spray-water input. Air velocity, 280 miles per hour; mean droplet diameter, 10-15 microns.

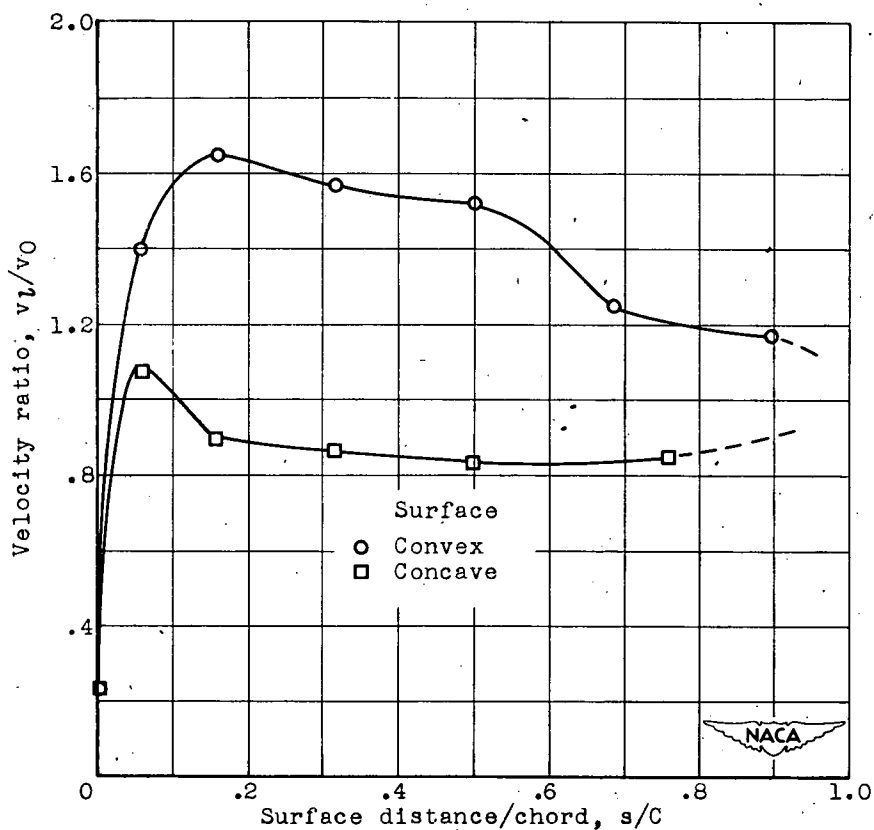


Figure 4. - Chordwise variation of local air velocity. Inlet-air velocity, 302 miles per hour; total air temperature, 94° F.

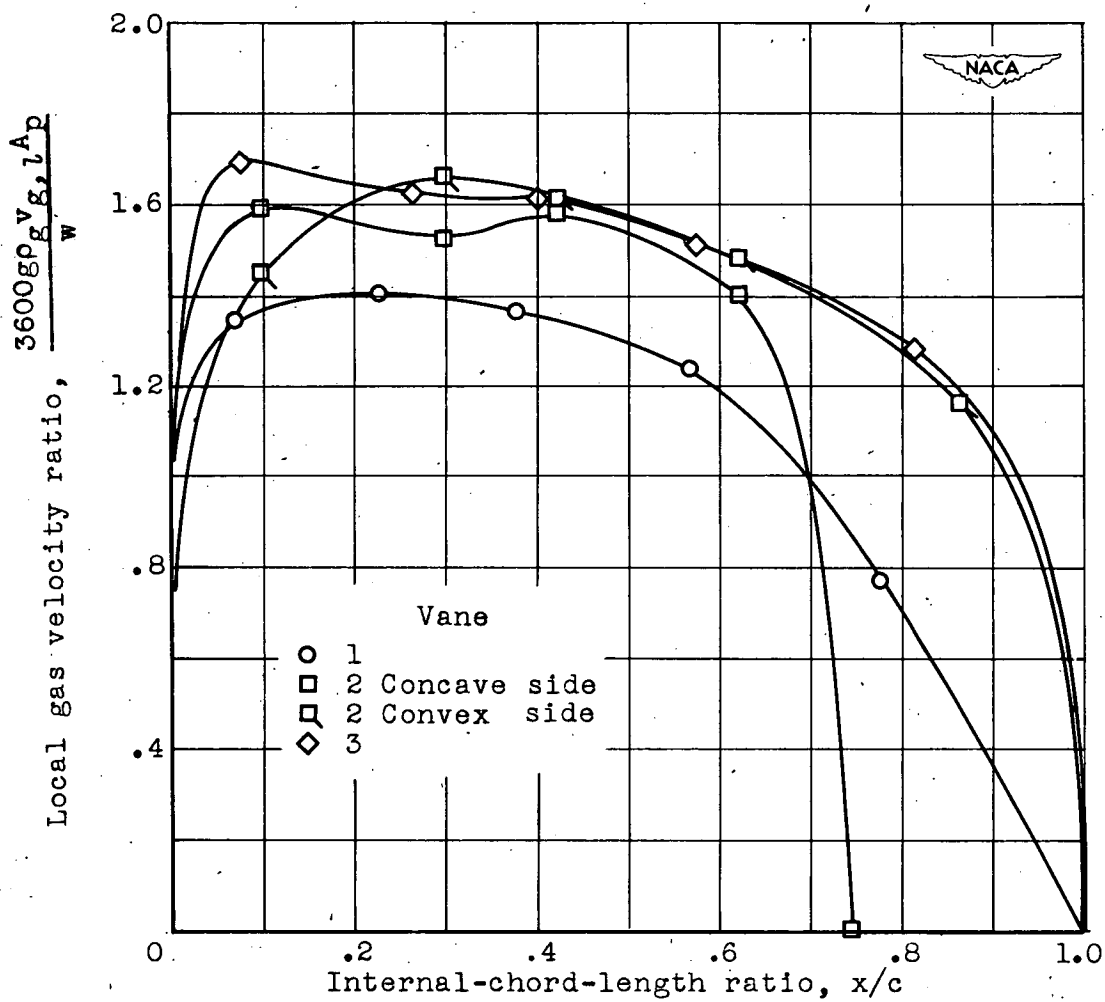
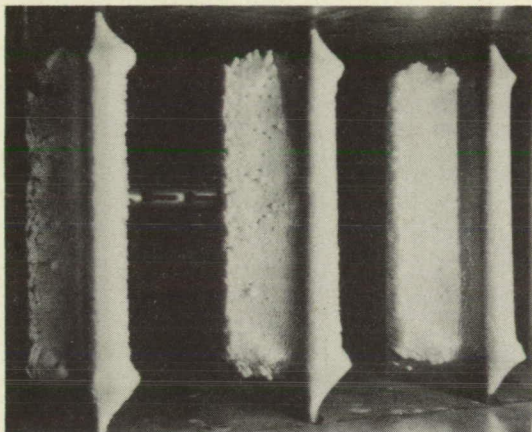


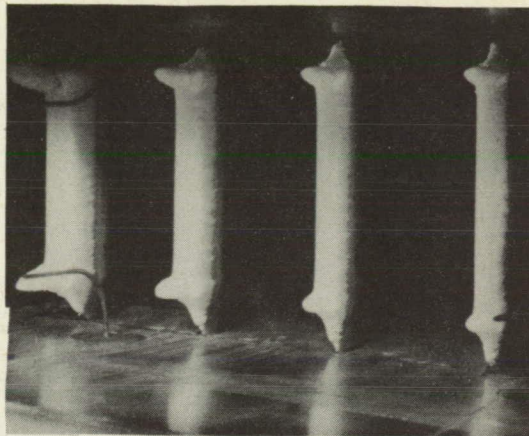
Figure 5. - Chordwise variation of internal gas velocity.

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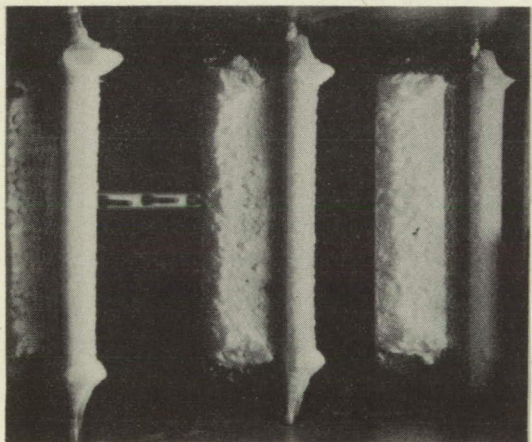
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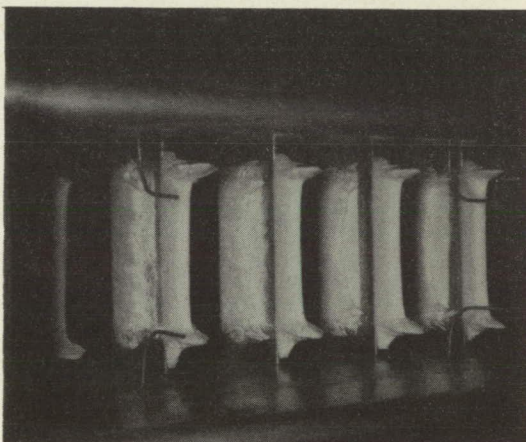
(a) Air velocity, 180 miles per hour;
air total temperature, 0° F; water
content, 0.4 gram per cubic meter; icing
time, $11\frac{1}{2}$ minutes.



(b) Air velocity, 180 miles per hour;
air total temperature, 0° F; water
content, 0.9 gram per cubic meter;
icing time, 7 minutes.

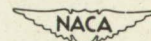


(c) Air velocity, 280 miles per hour;
air total temperature, 0° F; water
content, 0.4 gram per cubic meter;
icing time, 9 minutes.



(d) Air velocity, 280 miles per hour;
air total temperature, 0° F; water
content, 0.9 gram per cubic meter;
icing time, 11 minutes.

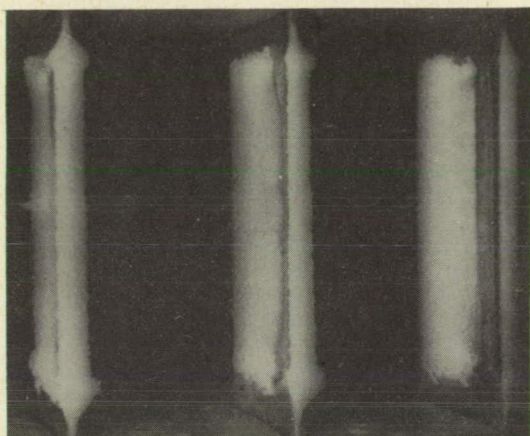
Figure 6. - Icing characteristics of unheated vanes.



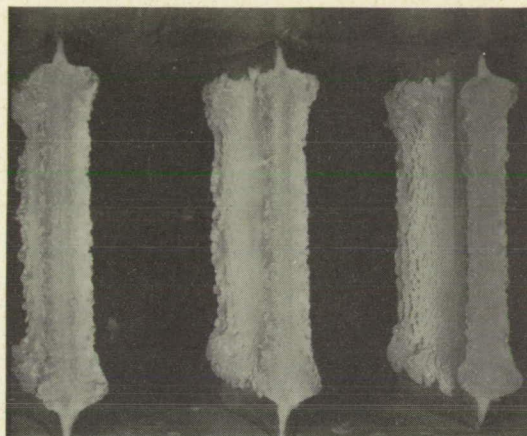
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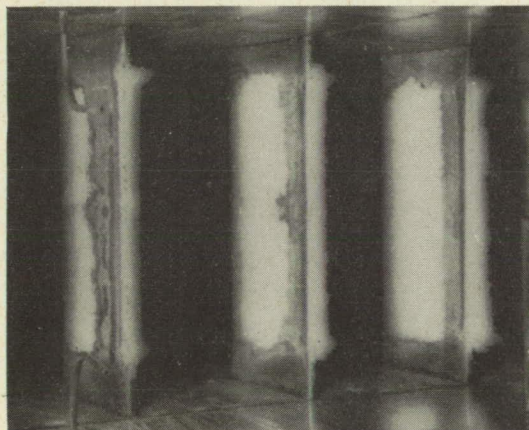
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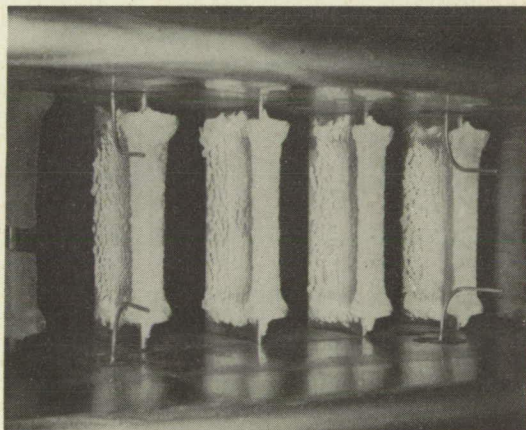
(e) Air velocity, 180 miles per hour;
air total temperature, 22° F; water
content, 0.4 gram per cubic meter;
icing time, 10 minutes.



(f) Air velocity, 180 miles per hour;
air total temperature, 22° F; water
content, 0.9 gram per cubic meter;
icing time, $3\frac{1}{2}$ minutes.



(g) Air velocity, 280 miles per hour;
air total temperature, 22° F; water
content, 0.4 gram per cubic meter;
icing time $4\frac{1}{2}$ minutes.



(h) Air velocity, 280 miles per hour;
air total temperature, 22° F; water
content, 0.9 gram per cubic meter;
icing time, 4 minutes.

Figure 6. - Concluded. Icing characteristics of unheated vanes.

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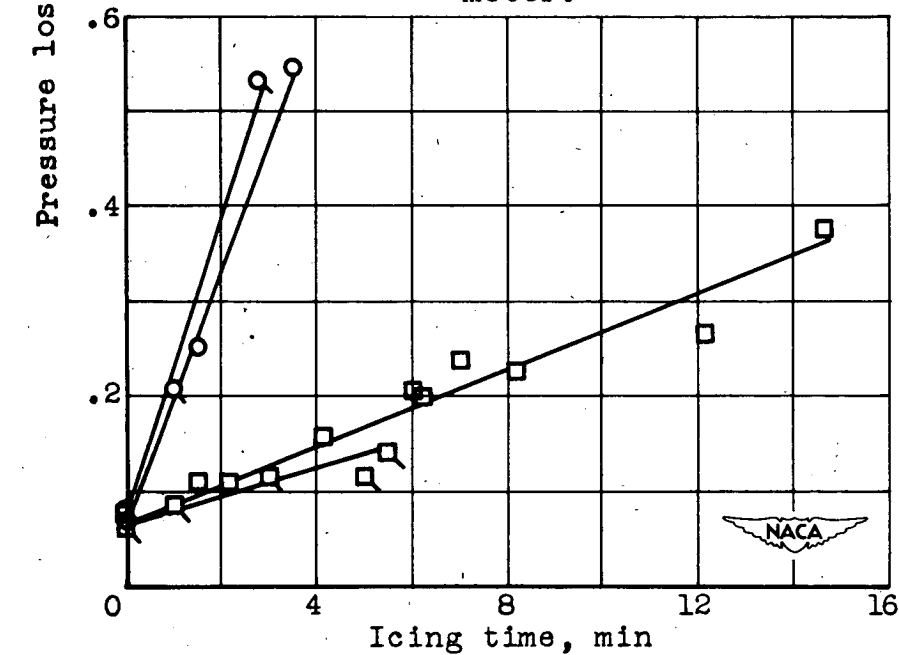
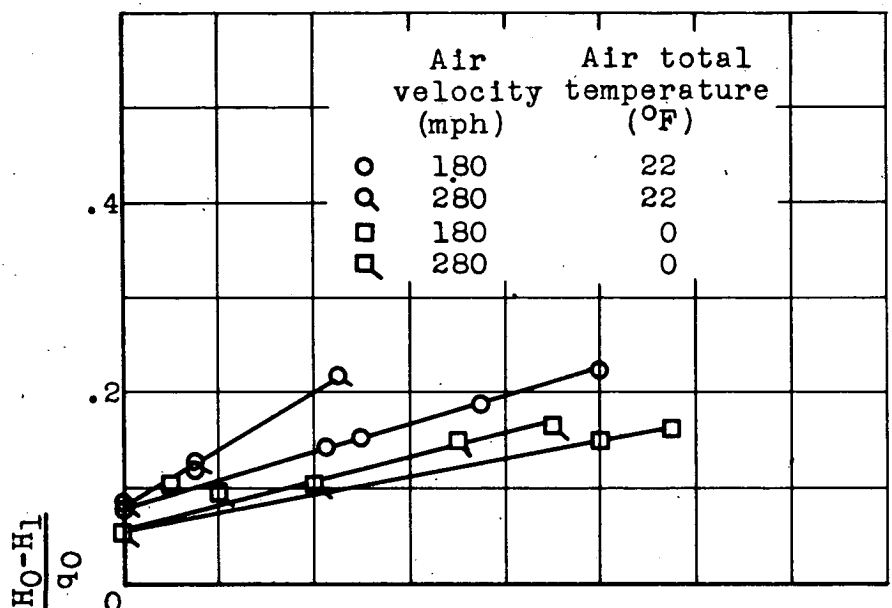
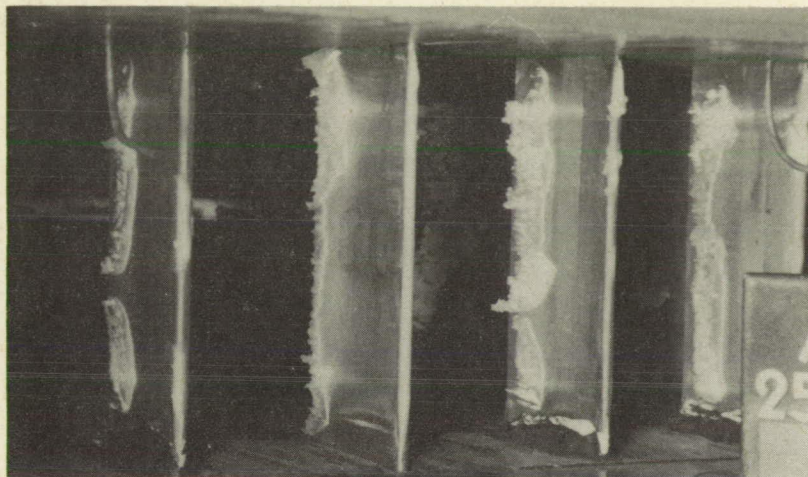


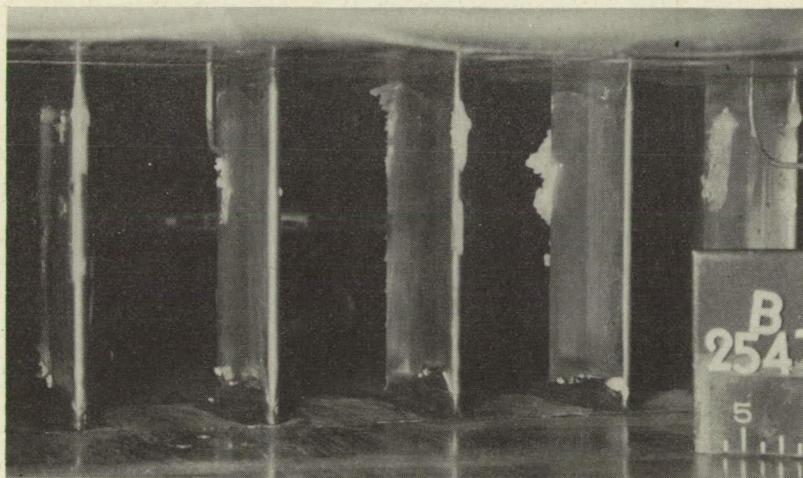
Figure 7. - Pressure loss across cascade of unheated guide vanes as function of icing time.

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(a) Air velocity, 280 miles per hour; air total temperature, 0° F; water content, 0.9 gram per cubic meter.



(b) Air velocity, 180 miles per hour; air total temperature, 0° F; water content, 0.9 gram per cubic meter.

Figure 8. - Typical icing with submarginal heating.

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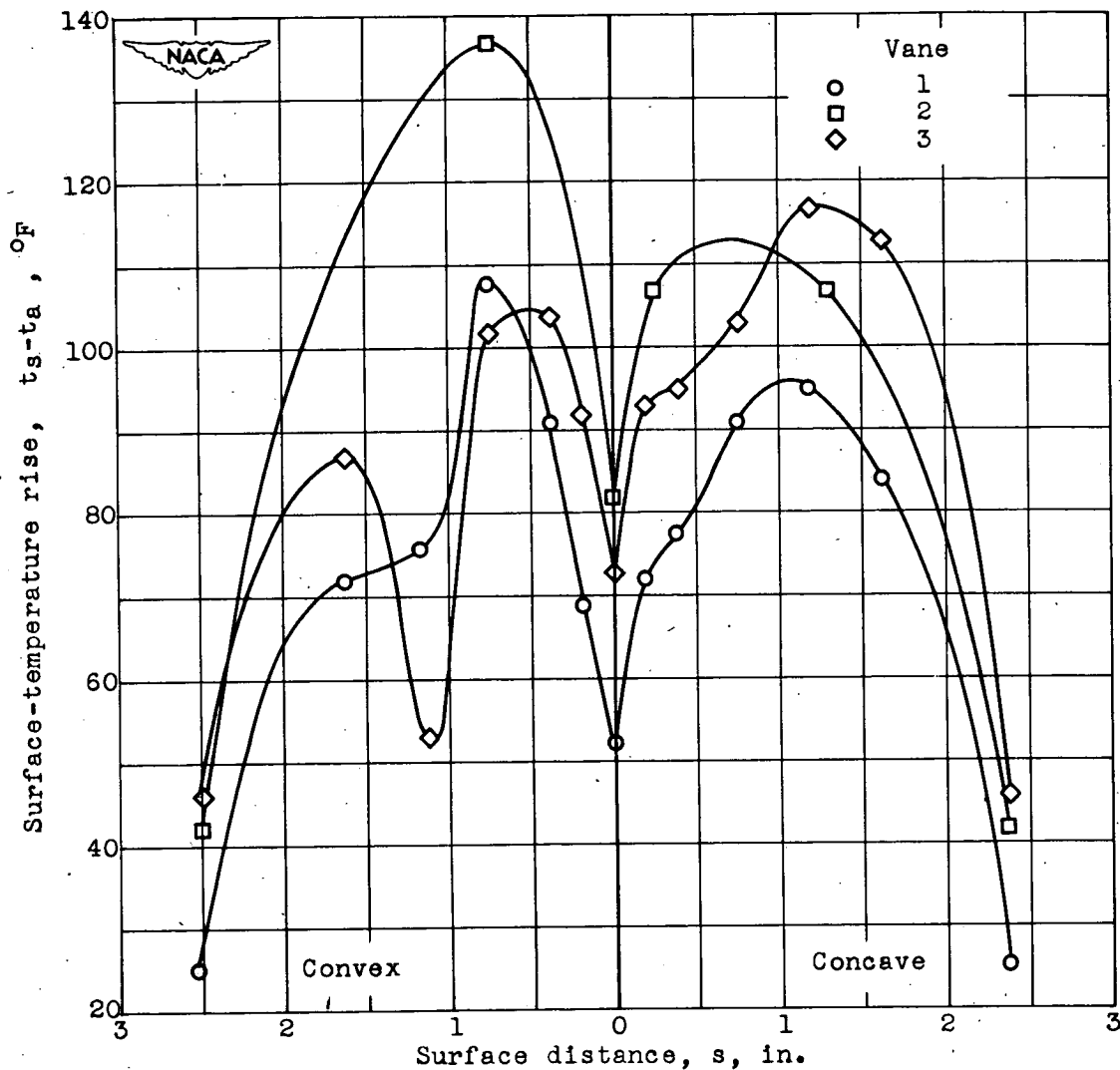


Figure 9. - Chordwise surface temperature rise in dry air flow for three gas-heated vanes. Air velocity, 298 miles per hour; gas flow, 120 pounds per hour; mean gas-temperature differential, $(t_{g,m} - t_a)$, 195° F.

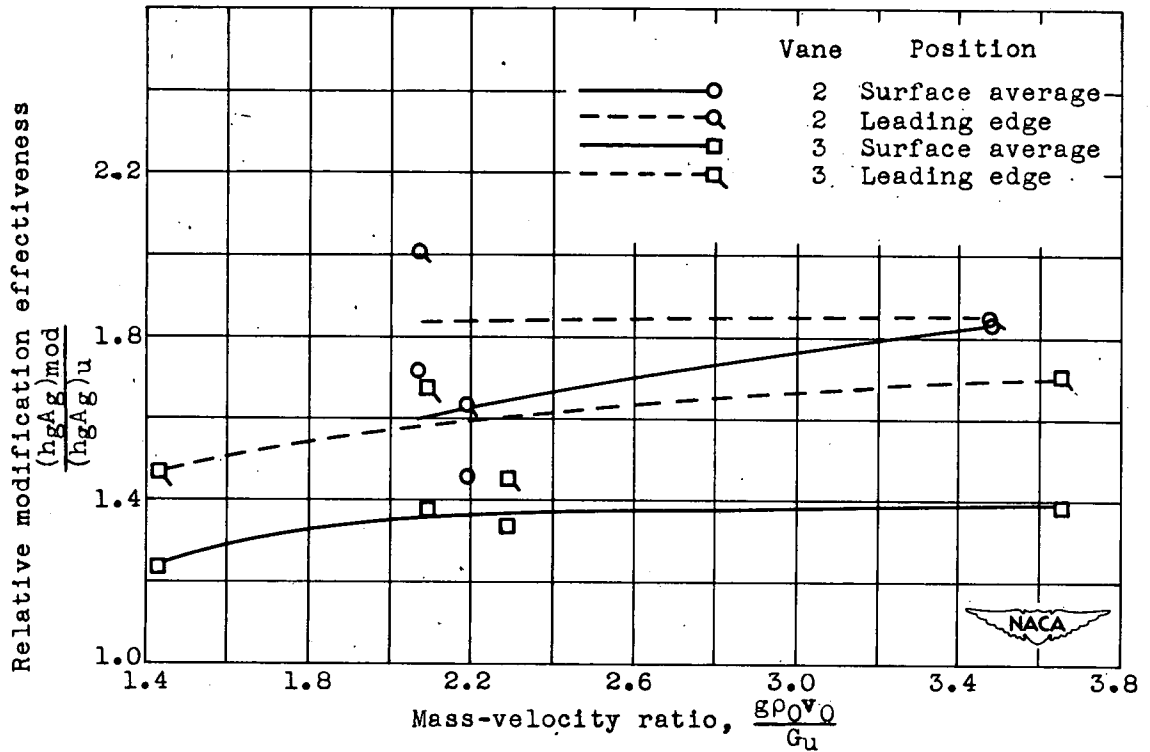
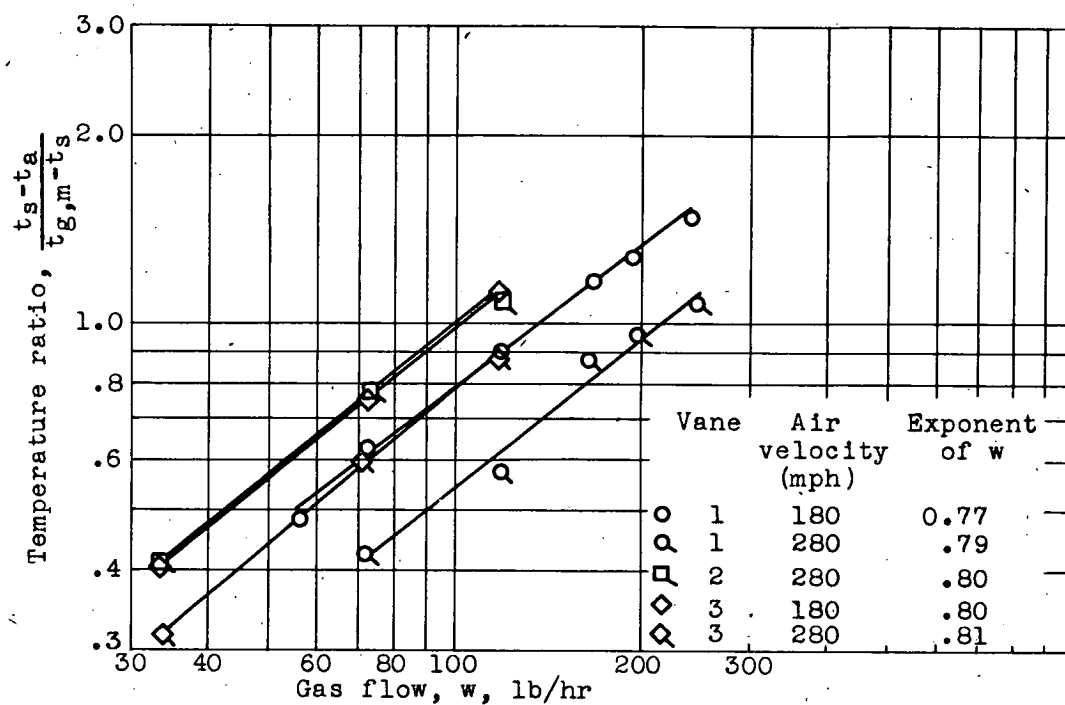
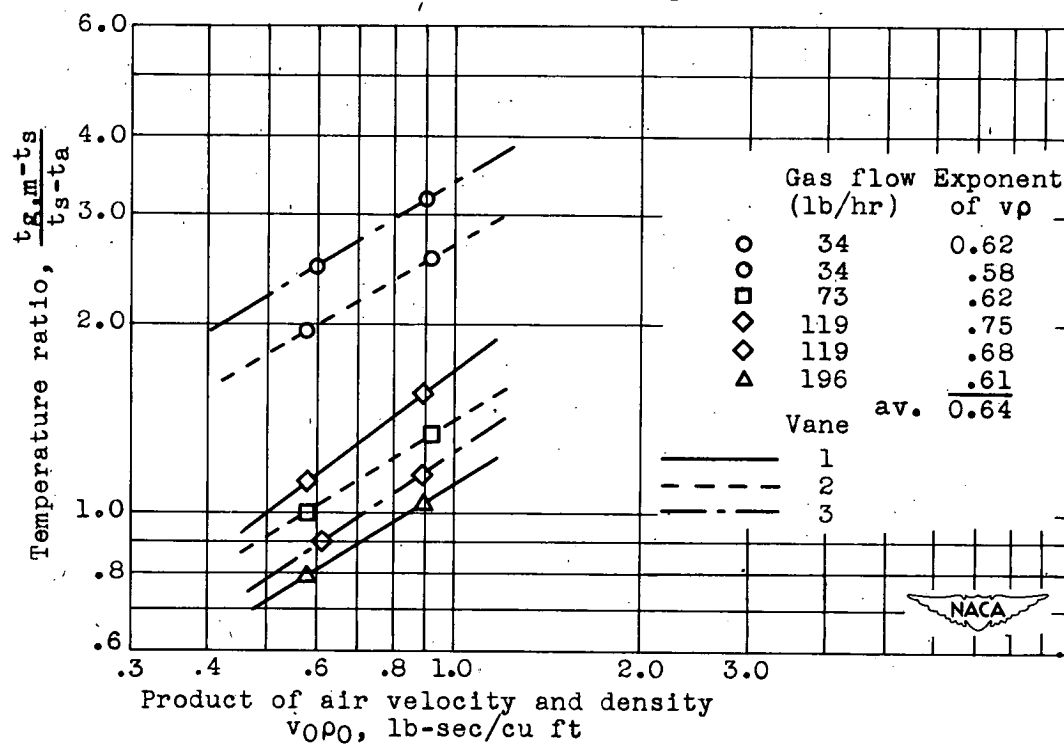


Figure 10. - Relative modification effectiveness of vanes 2 and 3 as function of mass velocity ratio.



(a) Gas-flow exponent.



(b) Air-flow exponent.

Figure 11. - Determination of internal and external flow exponents.

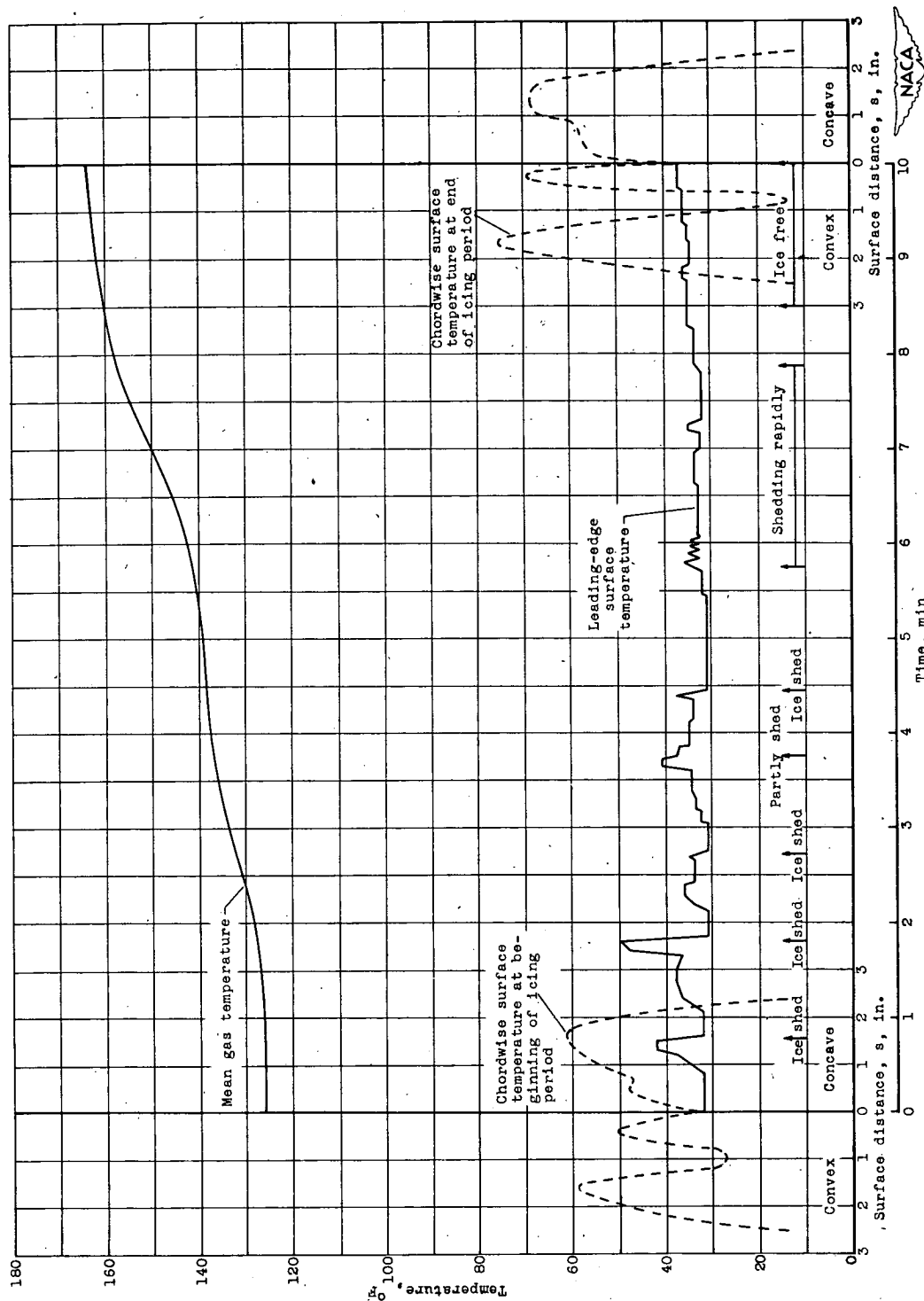


Figure 12. - Time-temperature variation of vane 3 leading edge in icing condition with heating rate increased through marginal level. Air velocity, 280 miles per hour; datum air temperature, 00°F; water content, 0.9 gram per cubic meter; gas flow, 145 pounds per hour.

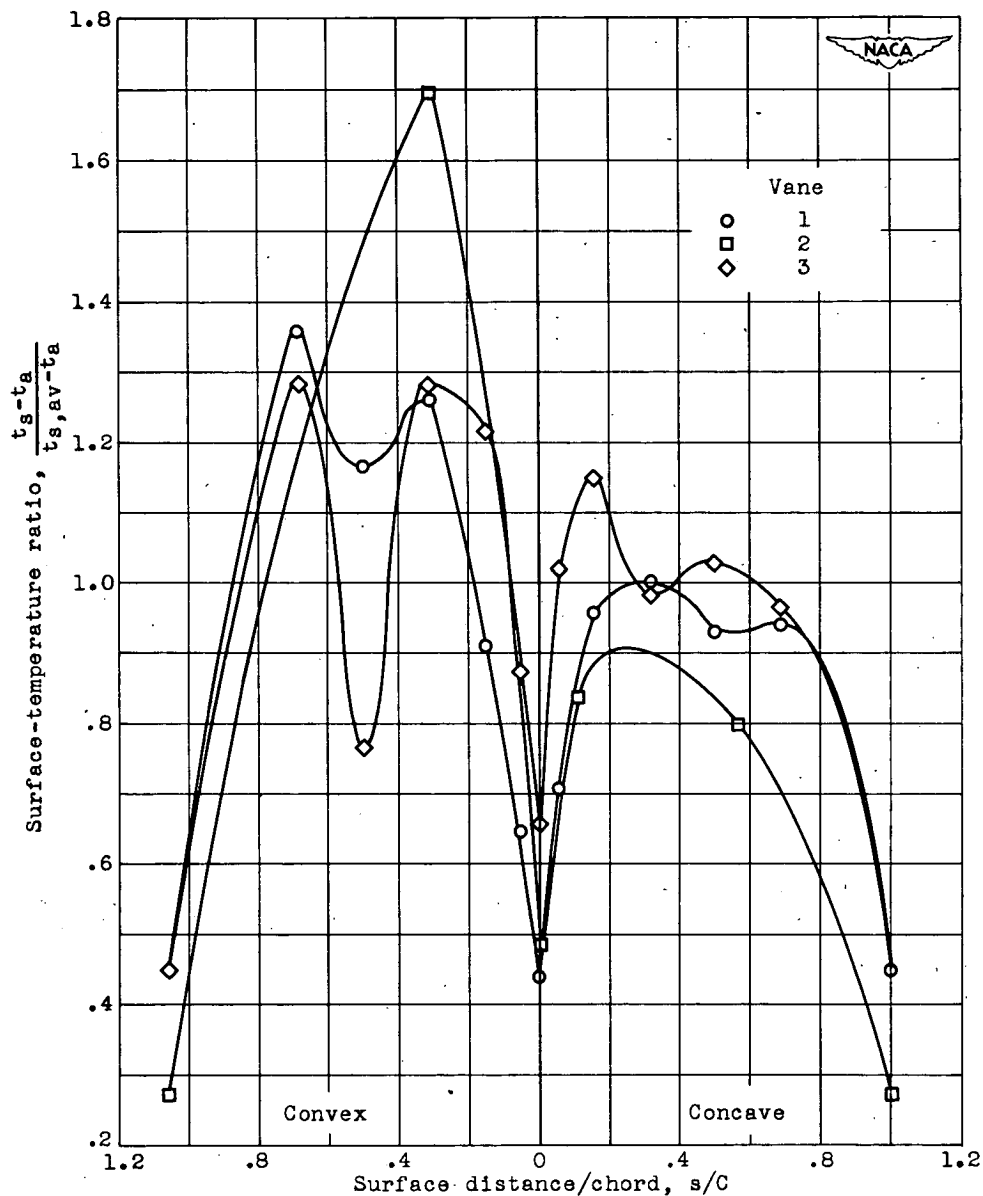


Figure 13. - Chordwise surface-temperature distribution for three vanes in icing condition with heating in excess of anti-icing requirement. Air velocity, 280 miles per hour; datum air temperature, 0°F ; water content, 0.9 gram per cubic meter.

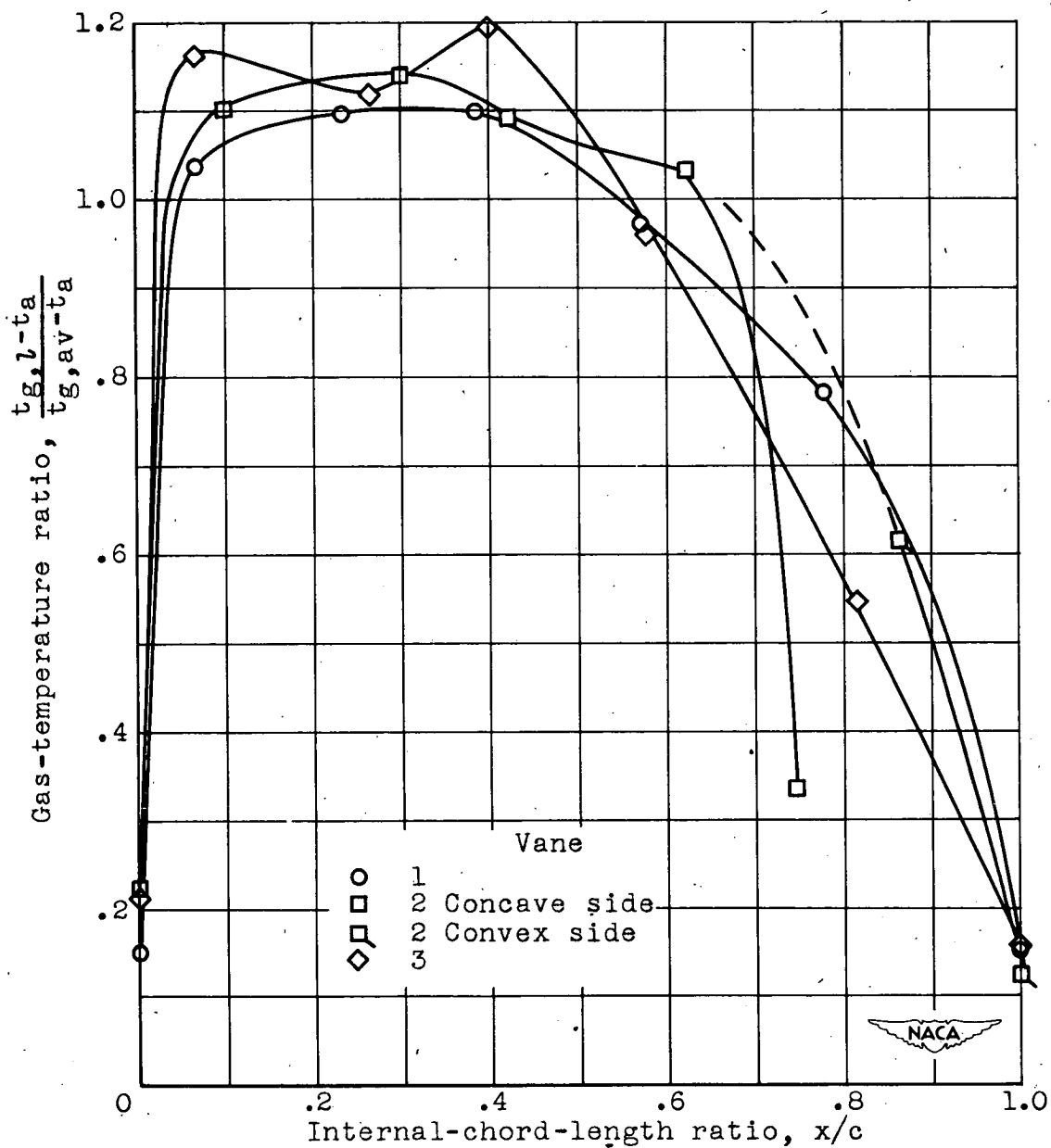
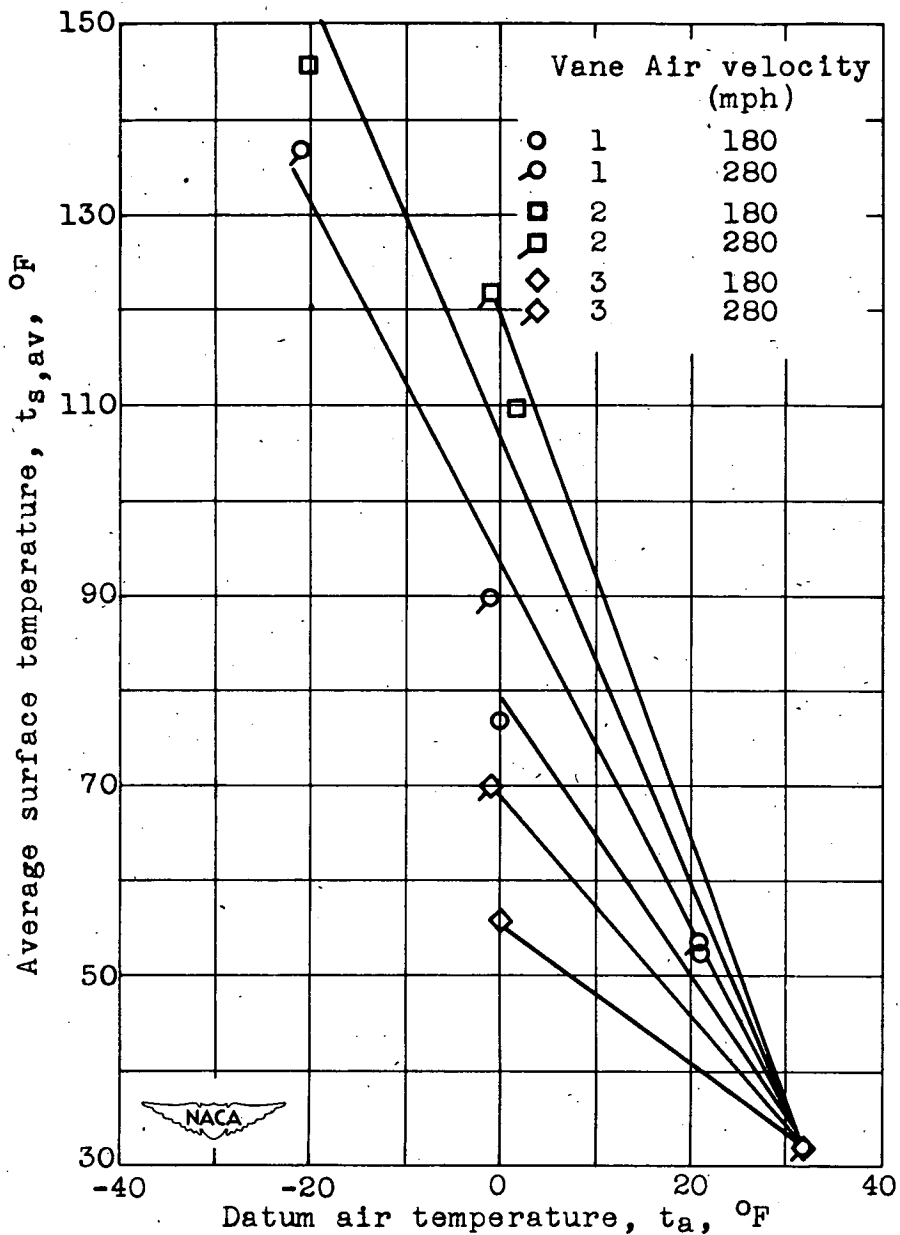
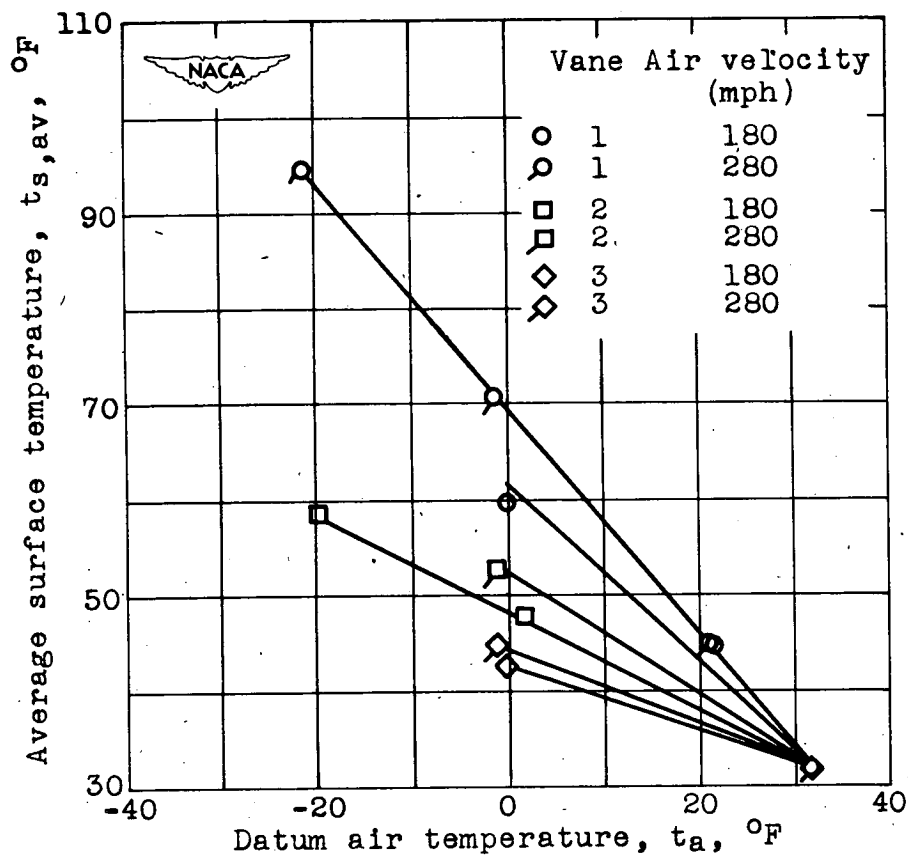


Figure 14. - Chordwise distribution of internal gas temperature for three vanes. Air velocity, 280 miles per hour; datum air temperature, 0° F; water content, 0.9 gram per cubic meter.



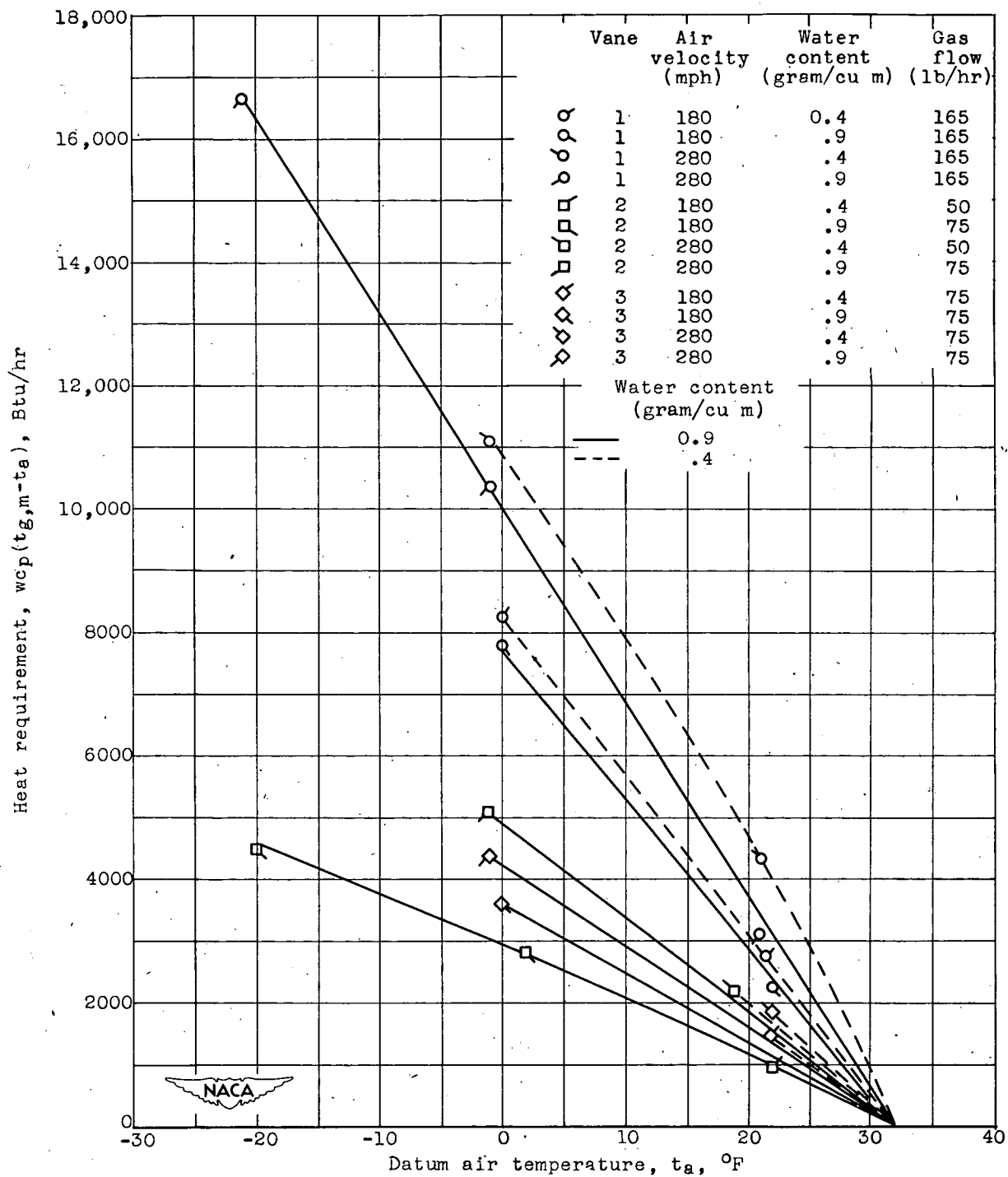
(a) Ice-free trailing-edge condition.

Figure 15. - Effect of datum air temperature on average chordwise surface temperature of three inlet guide vanes with marginal anti-icing. Water content, 0.9 gram per cubic meter.



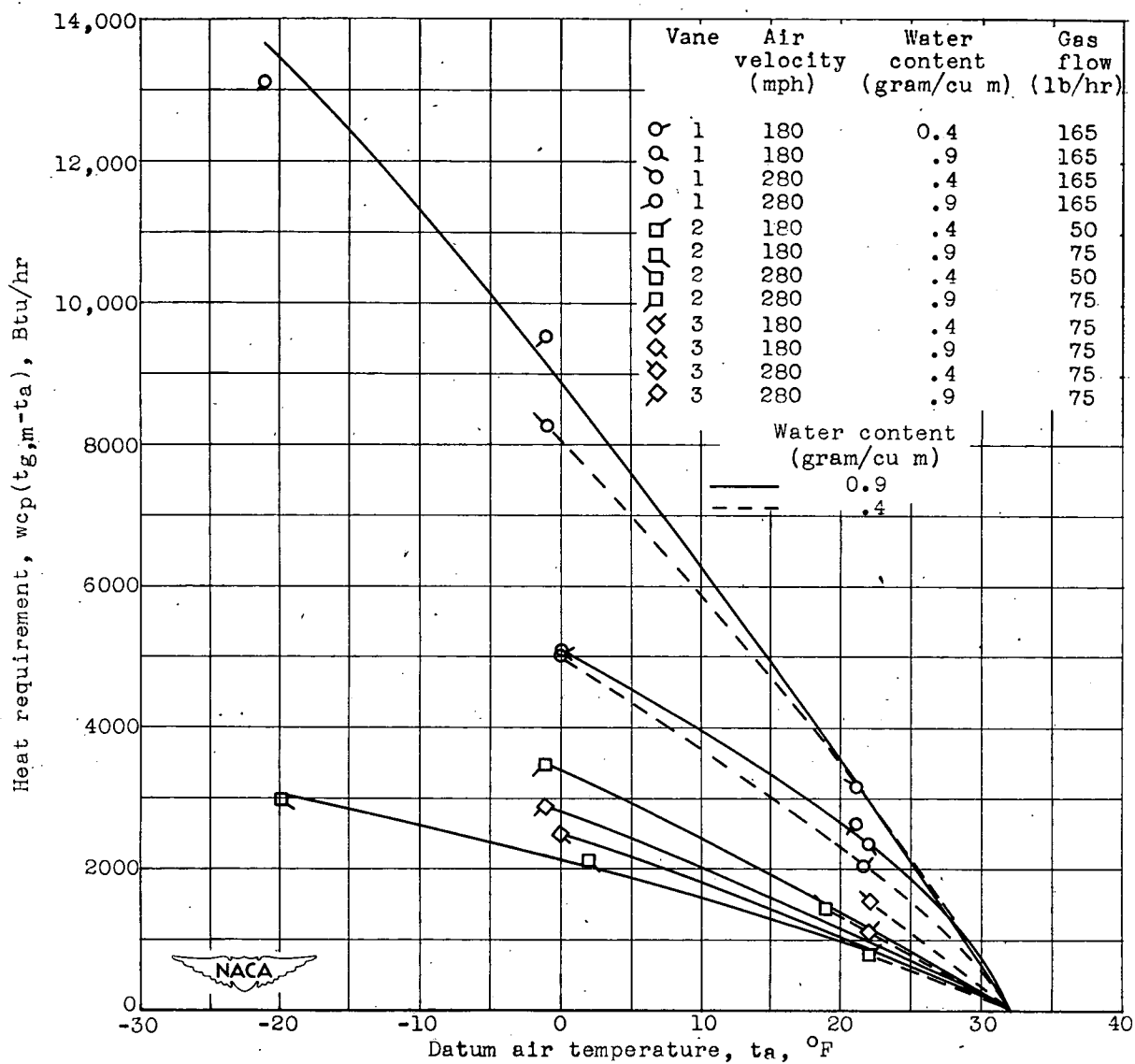
(b) Ice-free leading-edge condition.

Figure 15. - Concluded. Effect of datum air temperature on average chordwise surface temperature of three inlet guide vanes with marginal anti-icing. Water content, 0.9 gram per cubic meter.



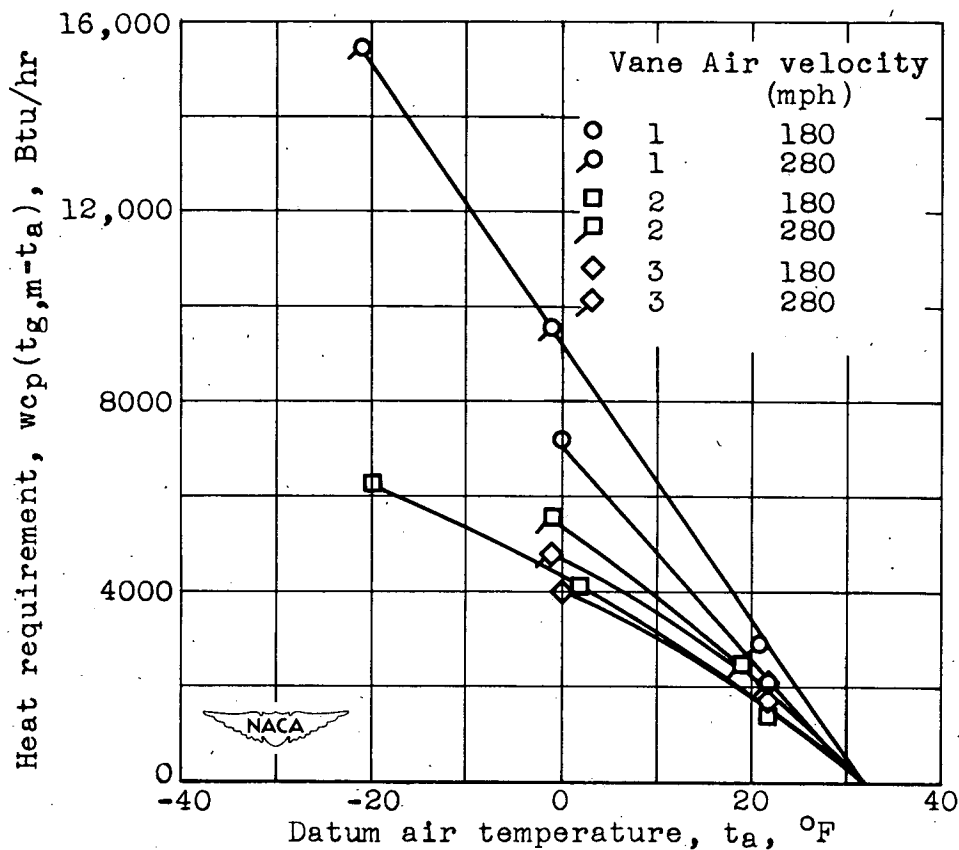
(a) Ice-free trailing-edge condition.

Figure 16. - Heat requirements at various gas flows for marginal anti-icing at midspan of three vanes.



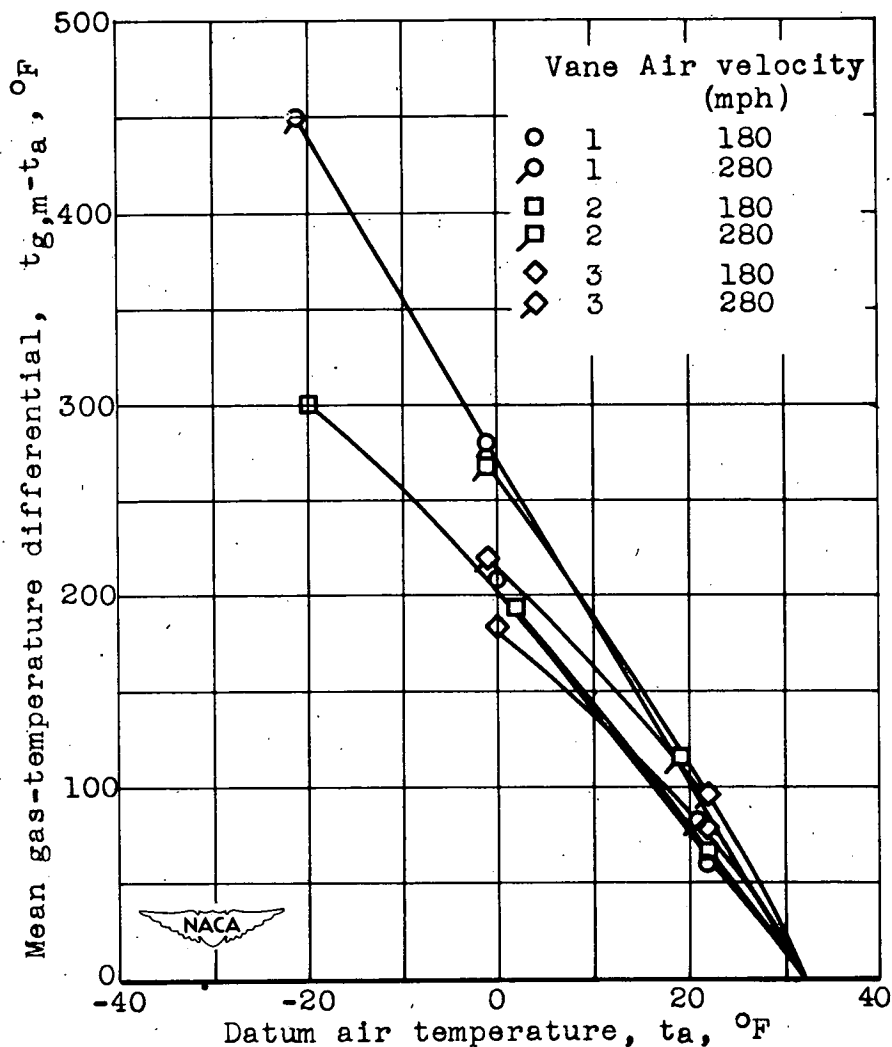
(b) Ice-free leading-edge condition.

Figure 16. - Concluded. Heat requirements at various gas flows for marginal anti-icing at midspan of three vanes.



(a) Marginal heat requirement, $wcp(t_{g,m}-t_a)$.

Figure 17. - Comparison for three vanes of marginal requirements for ice-free trailing edges at midspan. Nominal water content, 0.9 gram per cubic meter; assumed gas flow per unit internal area, 6×10^4 pounds per hour per square foot.



(b) Mean gas-temperature differential requirement, $t_{g,m}-t_a$.

Figure 17. - Concluded. Comparison for three vanes of marginal requirements for ice-free trailing edges at midspan. Nominal water content, 0.9 gram per cubic meter; assumed gas flow per unit internal area, 6×10^4 pounds per hour per square foot.

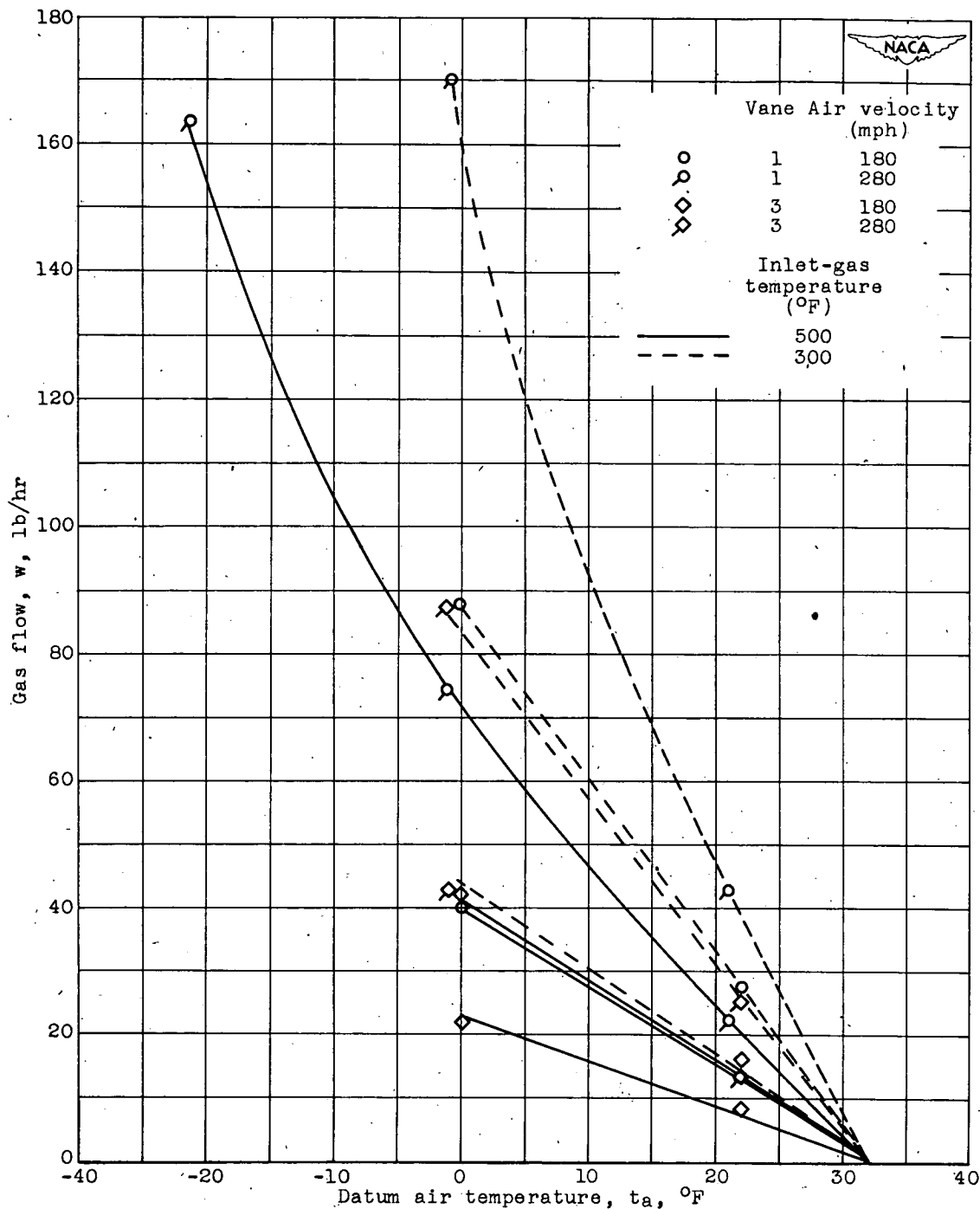


Figure 18. - Calculated gas flow required to maintain full spanwise and chordwise ice prevention with inlet-gas temperature assumed constant at 300° and 500° F. Nominal water content, 0.9 gram per cubic meter.

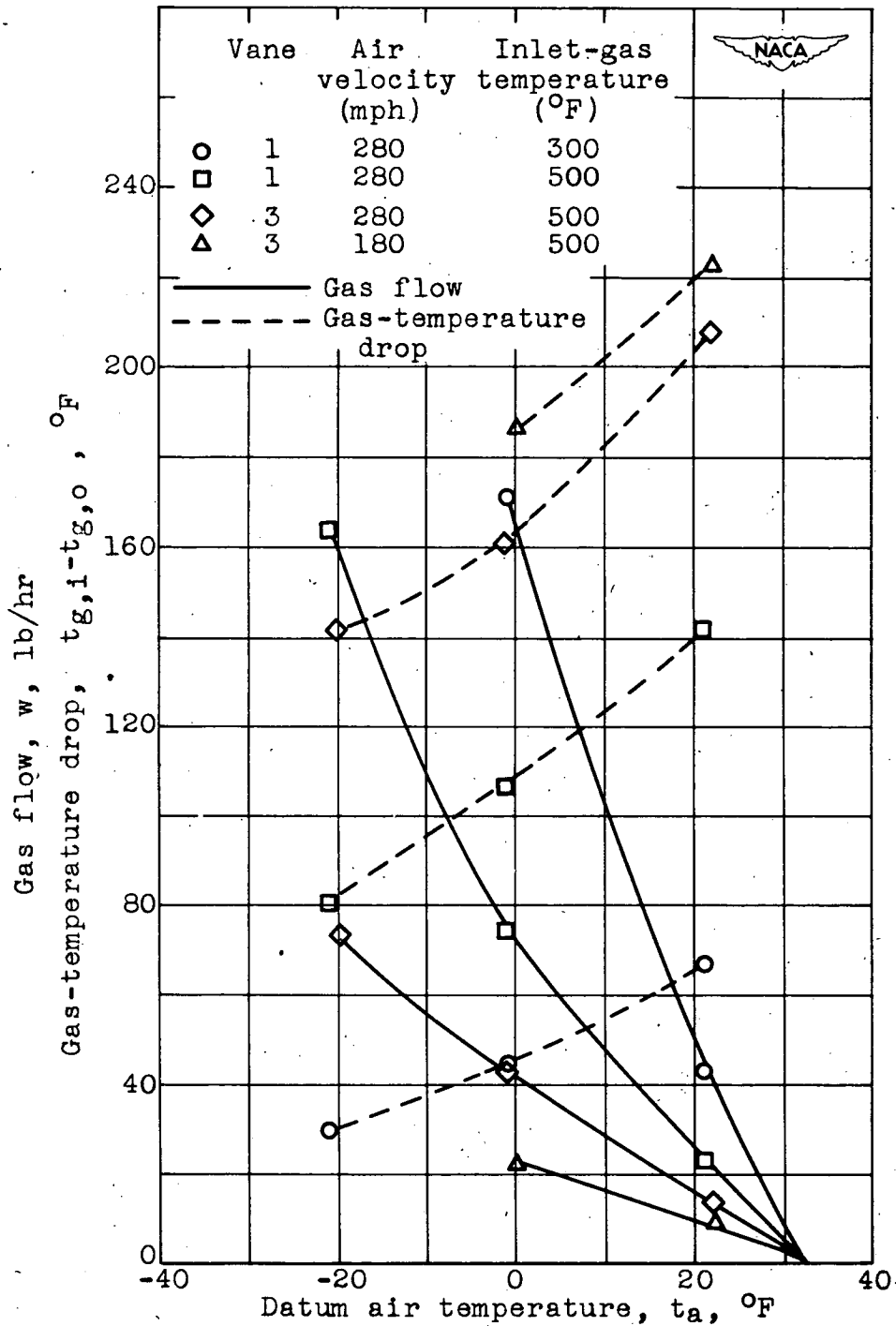


Figure 19. - Typical calculated values of gas flow and gas-temperature drop for two completely ice-free vanes as function of datum air temperature. Nominal water content, 0.9 gram per cubic meter.

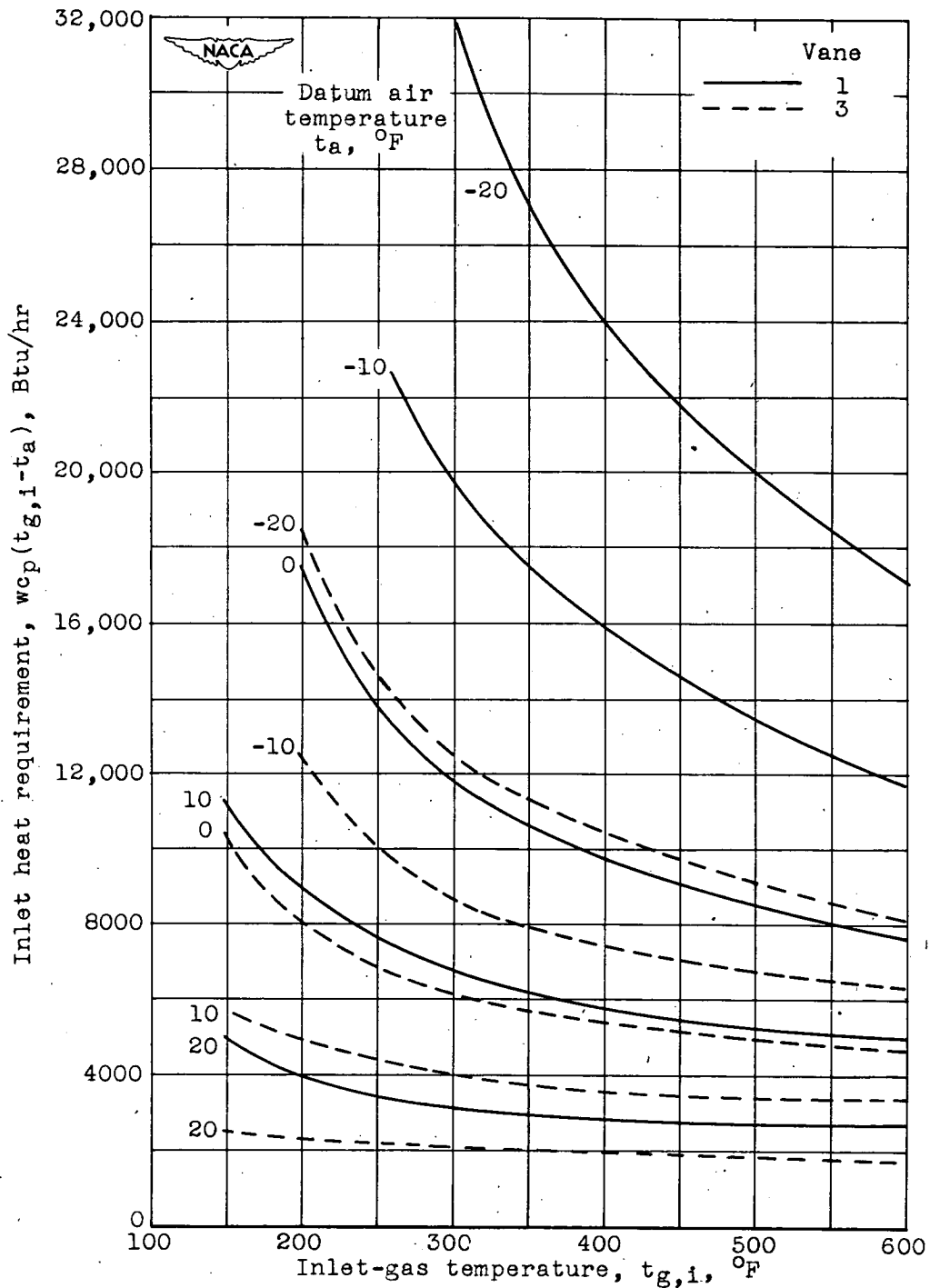
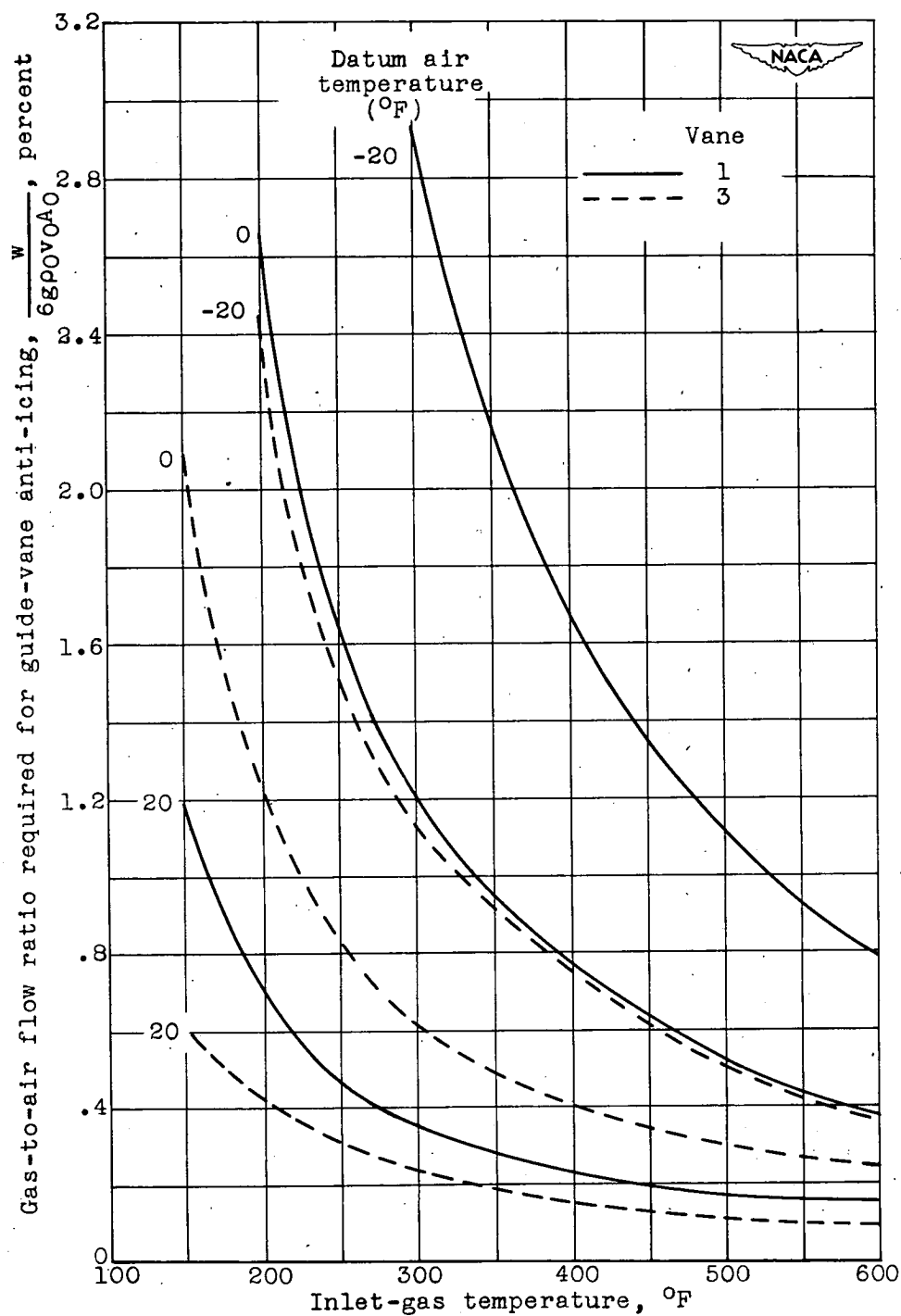
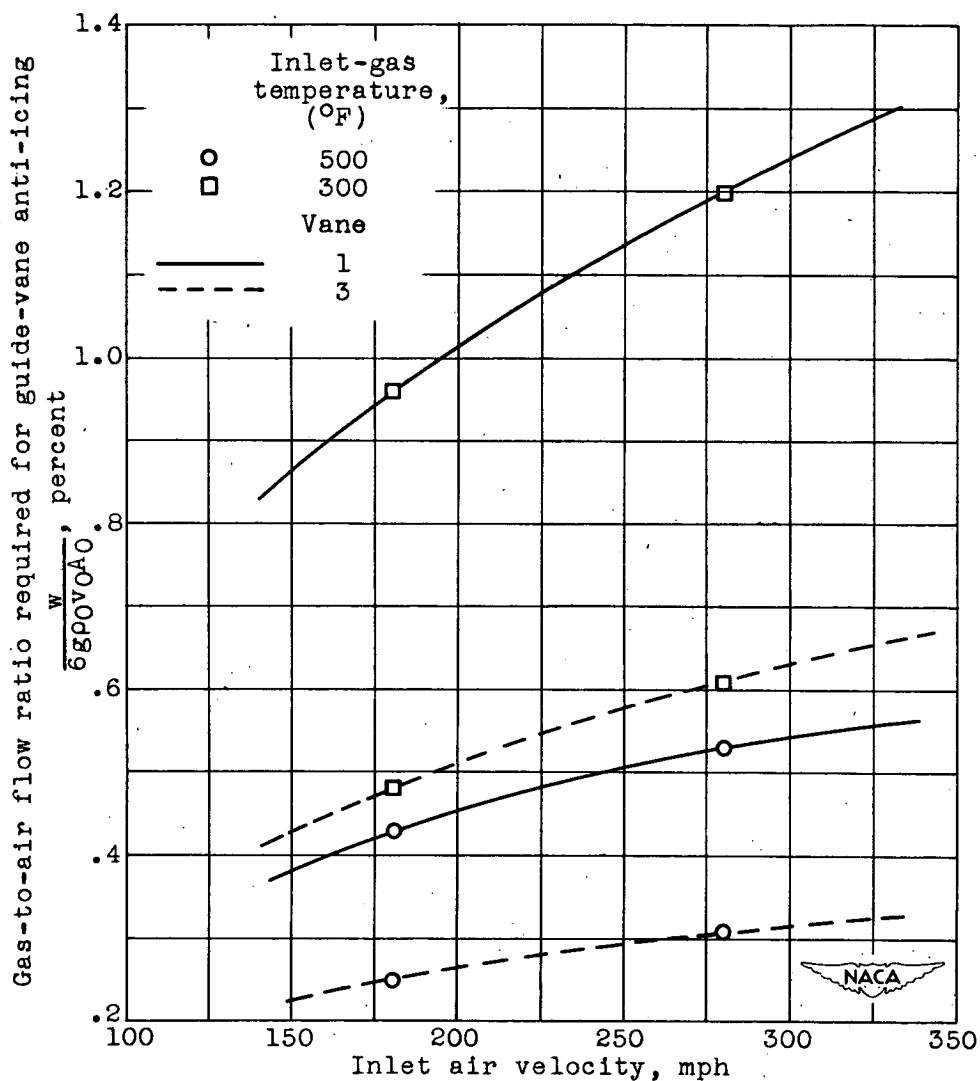


Figure 20. - Calculated heat input required for complete ice prevention on vanes 1 and 3 as function of inlet-gas temperature for range of datum air temperatures. Air velocity, 280 miles per hour; nominal water content, 0.9 gram per cubic meter.



(a) Variation with inlet-gas temperature. Air velocity, 280 miles per hour; nominal water content, 0.9 gram per cubic meter.

Figure 21. - Gas flow, expressed in percentage of inlet-air flow, required for heating inlet-guide-vane stage for complete ice prevention.



(b) Variation with inlet-air velocity. Datum air temperature, 0° F; nominal water content, 0.9 gram per cubic meter.

Figure 21. - Concluded. Gas flow, expressed in percentage of inlet-air flow, required for heating inlet-guide-vane stage for complete ice prevention.